RHIC Results on J/ψ

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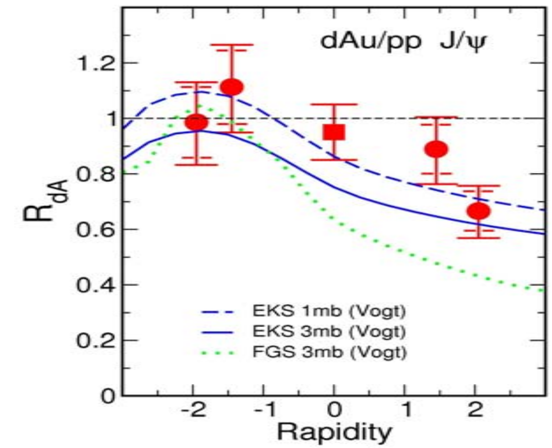
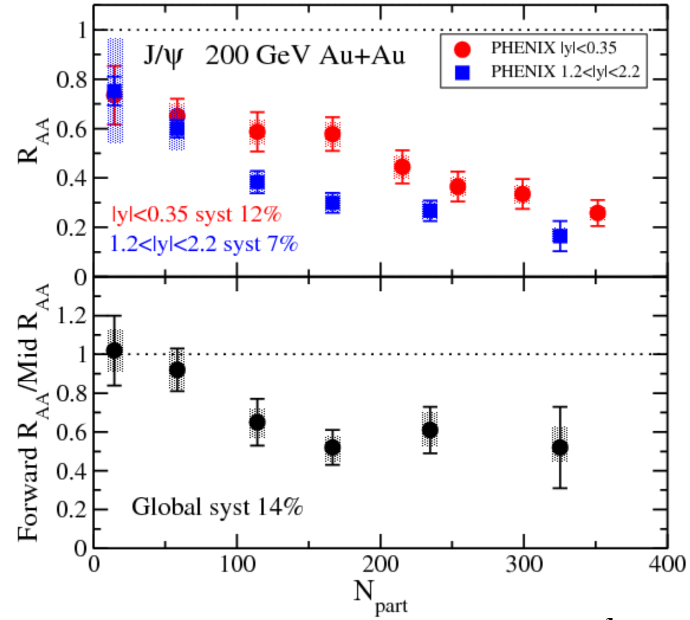
QM06 - Shanghai – 18 November 2006

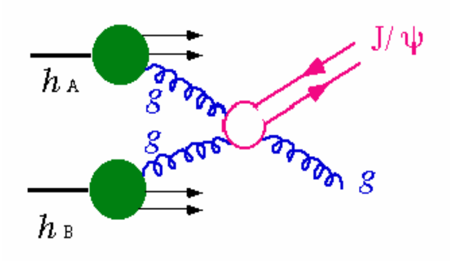
- Production
  - cross section & polarization
  - feed-down
- Cold nuclear matter (CNM)
  - shadowing or gluon saturation
  - absorption & gluon energy loss
  - p_T broadening
  - lack of x_2 scaling
- Hot-dense matter in A+A collisions
  - final PHENIX AuAu results
  - cold nuclear matter effects in A+A
  - regeneration & sequential suppression
- Upsilons
- Summary

(see talks by A. Bickley, A. Glenn, T. Gunji on Saturday afternoon – 2.1)





J/ψ production, parton level structure & dynamics



Production of heavy vector mesons, J/ψ, ψ′ and ϒ

Gluon fusion dominates (NLO calculations add more complicated diagrams, but still mostly with gluons)

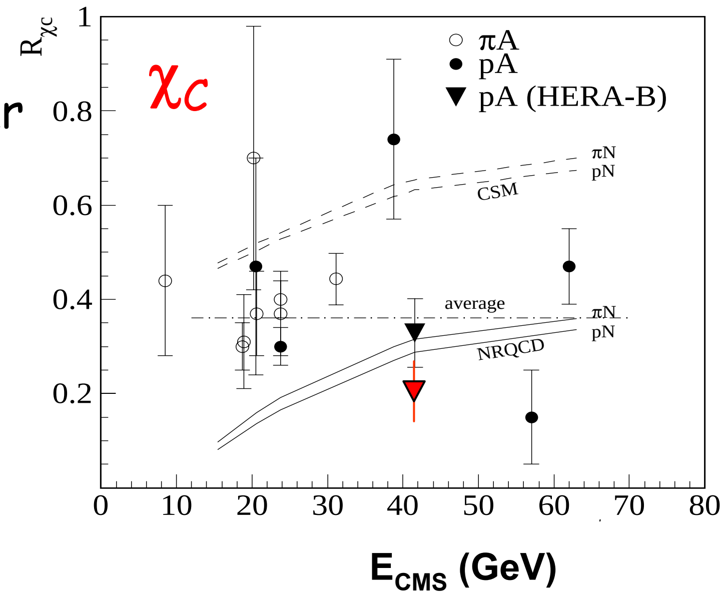
- color singlet or octet $c\bar{c}$: absolute cross section and polarization? Difficult to get both correct!

$\chi_{,1,2} \rightarrow J/\psi$	~30%
$\psi' \rightarrow J/\psi$	5.5%

Configuration of $c\bar{c}$ (important for pA cold nuclear matter effects)

Complications due to substantial feed-down from higher mass resonances, from ψ′, χ_c

- feed-down poorly known



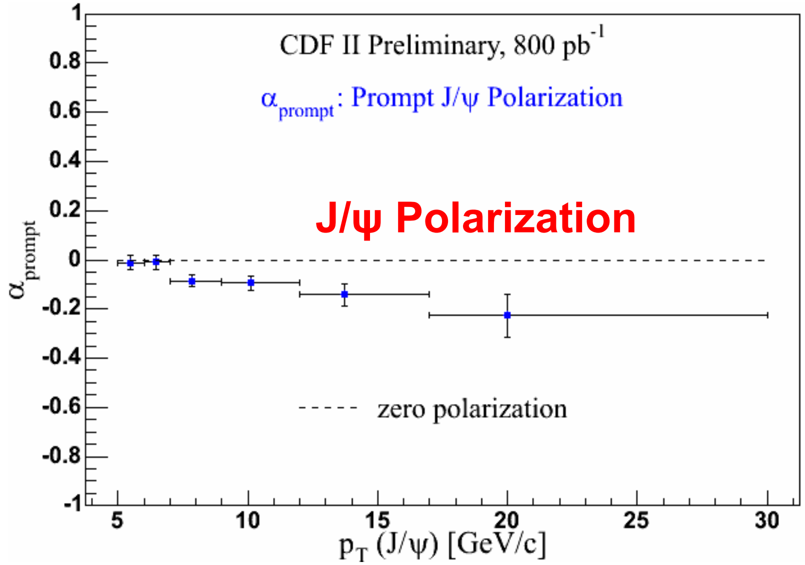
J/ψ Production - Polarization

- Octet models get correct cross section size (unlike singlet), but…
- CDF and Fermilab E866 J/ψ data show zero or longitudinal polarization & disagree with NRQCD predictions of large transverse polarization at large p_T

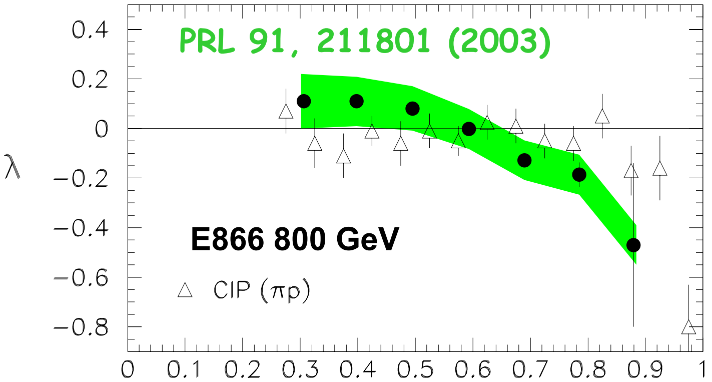
$$d\sigma/d\cos\theta = A(1+\lambda\cos^2\theta)$$

λ = +1 (transverse)
= -1 (longitudinal)

Is feed-down washing out polarization?
(~40% of J/ψ from feed-down)
(good ψ′ polarization measurement would be helpful here)



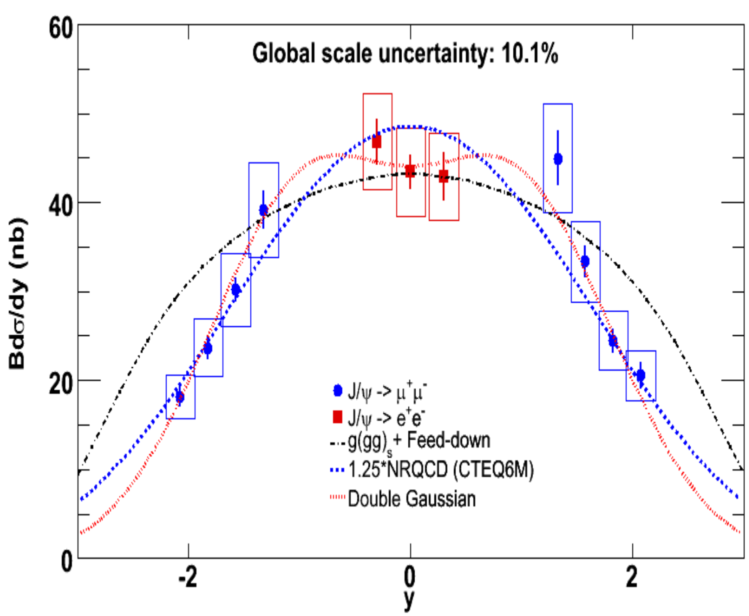
E866/NuSea



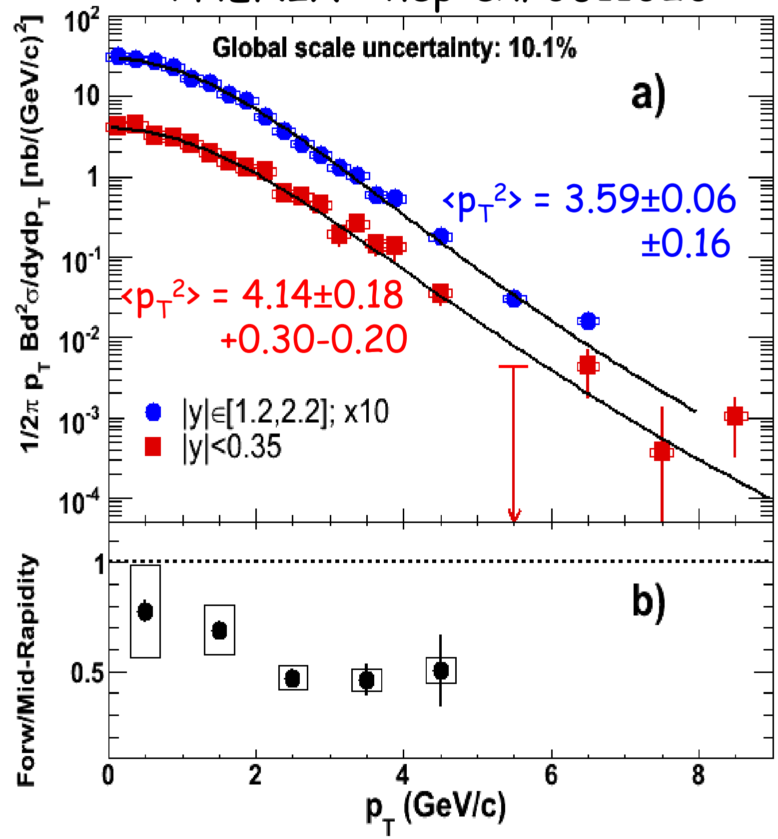
$x_F = x_1 - x_2$

PHENIX – p+p J/ψ – new run5 data

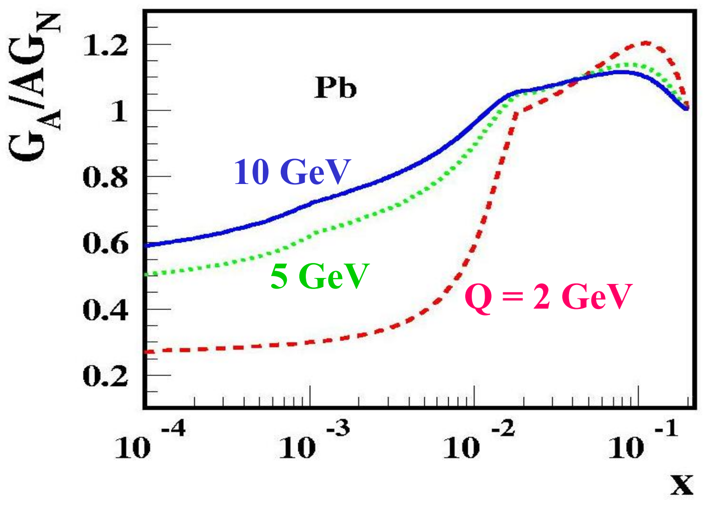
- Slightly favors flatter shape at mid-rapidity than most models
- Forward rapidity falloff steeper than 3-gluon pQCD model - black curve [Khoze et al. , Eur. Phys. J. C39, 163-171 (2005)]
- $BR \cdot \sigma_{tot} = 178 \pm 3 \pm 53 \pm 18$ nb
- Harder p_T than lower energy & softer at forward rapidity



PHENIX - hep-ex/0611020



Cold Nuclear Matter (CNM) Effects
Gluon Shadowing and Saturation

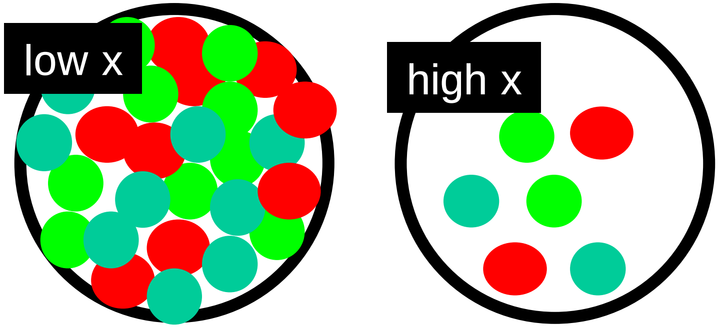


Leading twist gluon shadowing
- e.g. "FGS", Eur. Phys. J A5, 293 (1999)

Phenomenological fit to DIS & Drell-Yan data
- e.g. "EKS", Nucl. Phys. A696, 729 (2001).

Coherence approach and many others

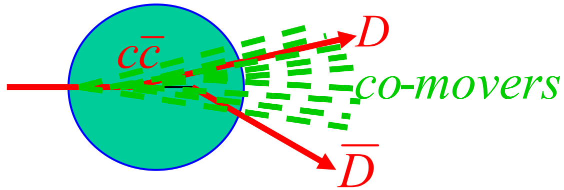
Amount of gluon shadowing differs by up to a factor of three between diff models!



Saturation or Color Glass Condensate (CGC) – see F. Gelis talk
- At low-x there are so many gluons that $2 \rightarrow 1$ diagrams become important and deplete low-x region
- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon

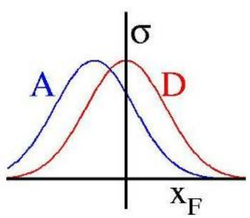
Cold Nuclear Matter Effects
Absorption & Energy Loss

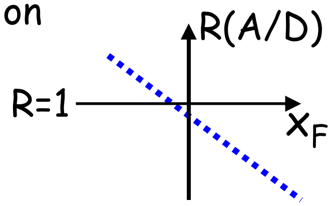
J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:



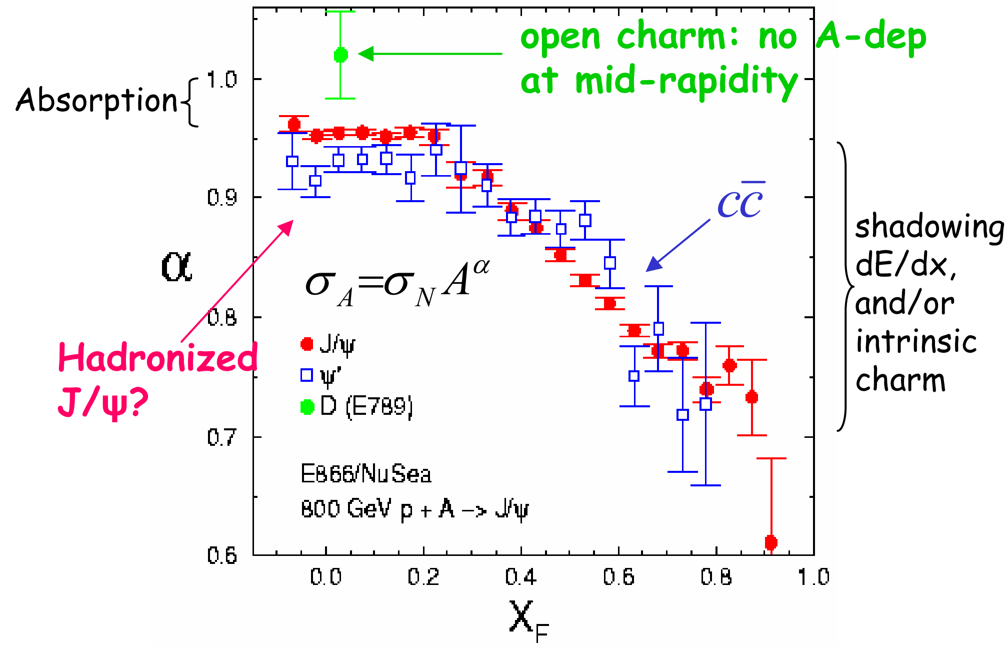
Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F



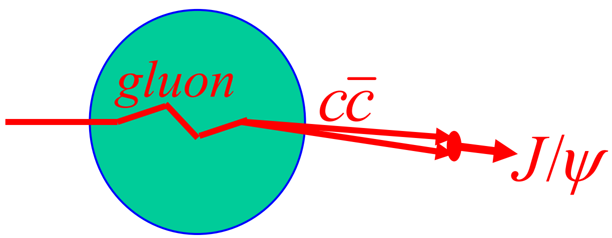


800 GeV p-A (FNAL)
PRL 84, 3256 (2000); PRL 72, 2542 (1994)



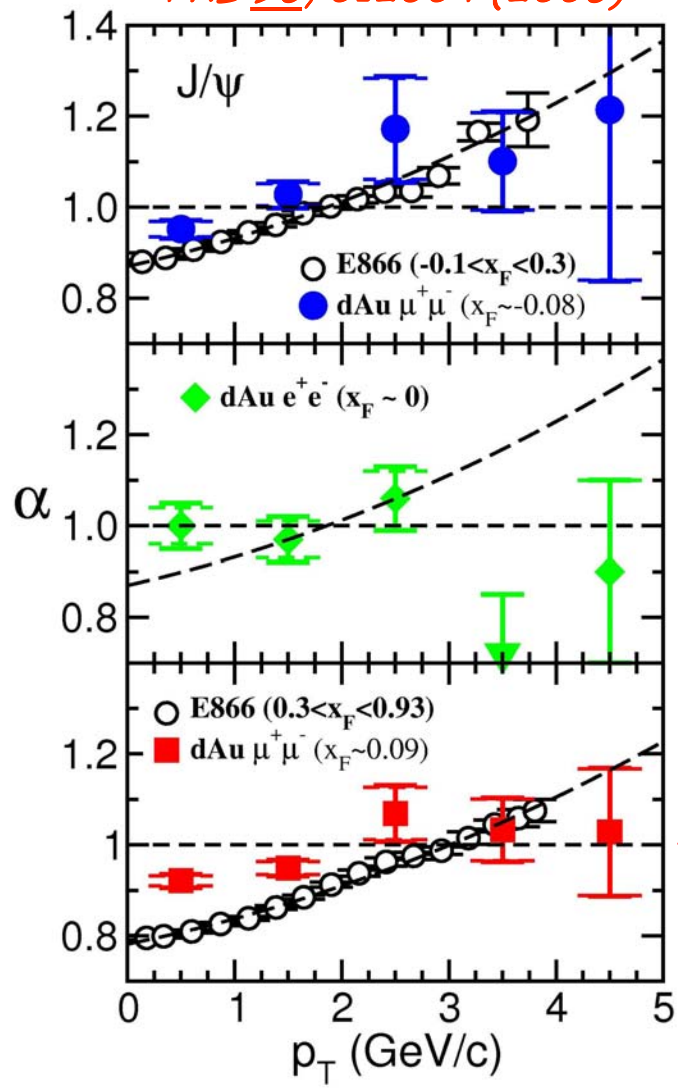
Cold Nuclear Matter
Transverse Momentum Broadening

$$\sigma_A = \sigma_N A^\alpha$$



Initial-state gluon multiple scattering causes p_T **broadening** (or Cronin effect)

PRL 96, 012304 (2006)

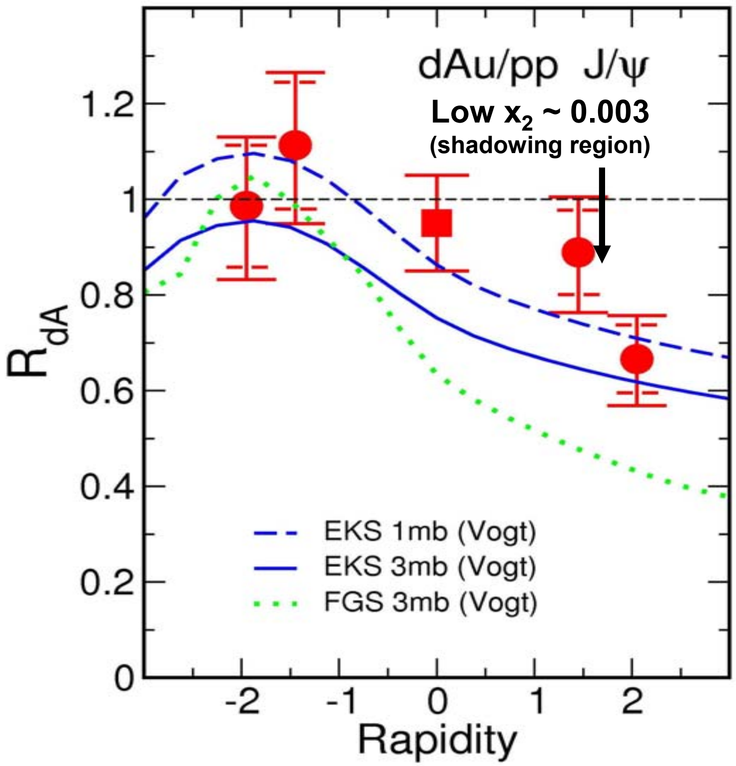


High x_2 ~ 0.09

PHENIX 200 GeV results show p_T broadening comparable to that at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

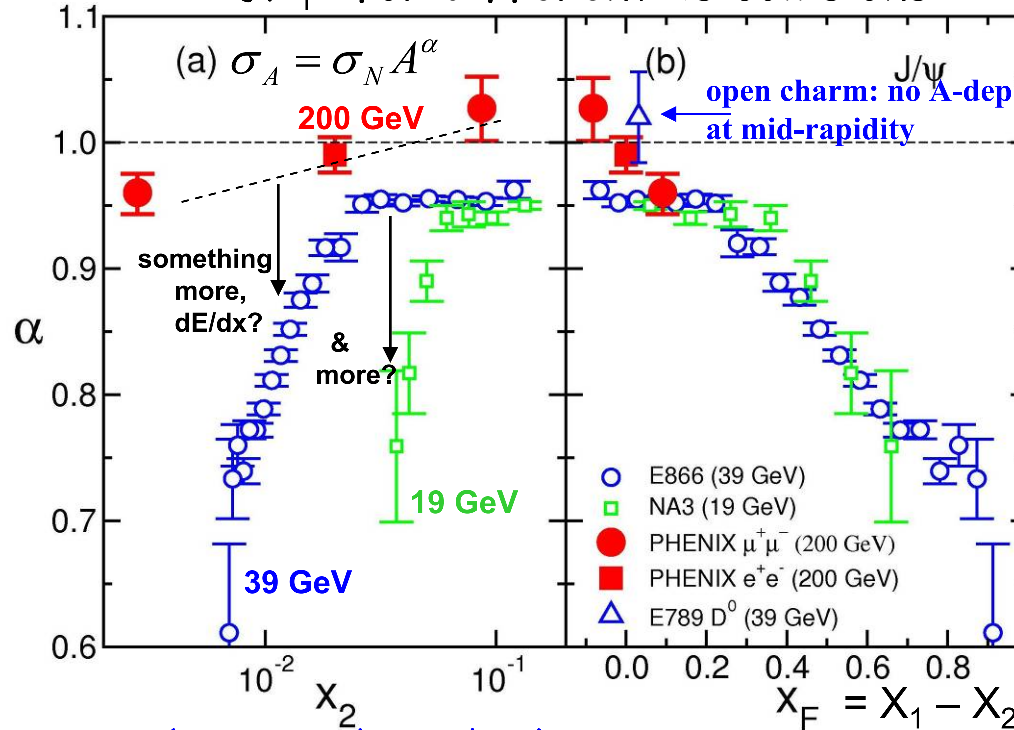
Low x_2 ~ 0.003

PHENIX J/ψ Nuclear Dependence
200 GeV dAu collisions – PRL 96, 012304 (2006)



Klein,Vogt, PRL 91:142301,2003

J/ψ for different √s collisions



(x_2 is x in the nucleus)

Data favors weak shadowing & absorption

- With limited statistics difficult to disentangle nuclear effects
- Need another dAu run!

Not universal vs x_2 as expected for shadowing, but does scale with x_F, why?

- initial-state gluon energy loss?
- Sudakov suppression (energy conservation)?

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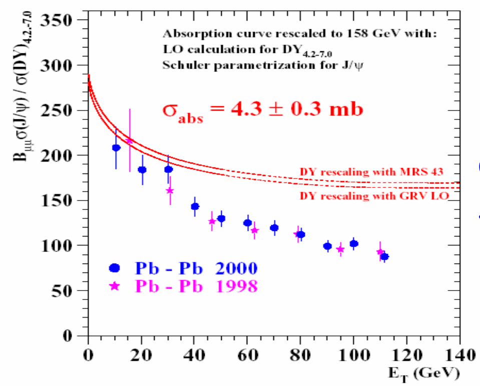
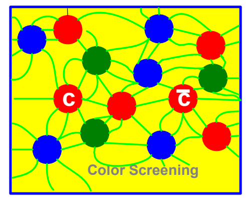
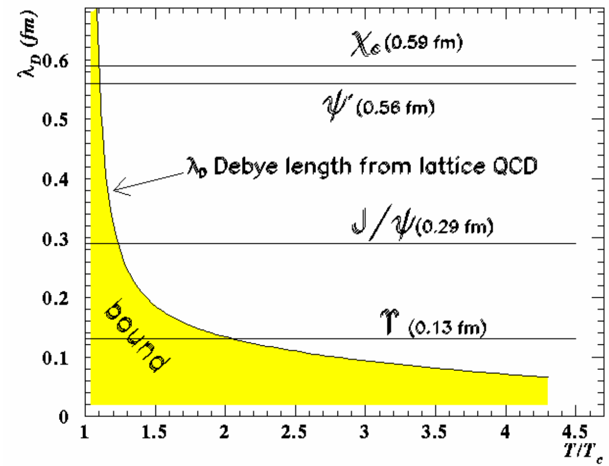
AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

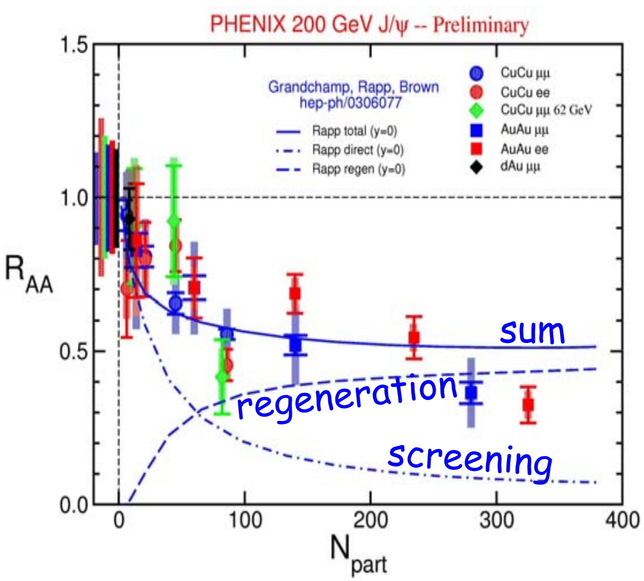
Debye screening predicted to destroy J/ψ's in a QGP with different states "melting" at different temperatures due to different binding energies.



NA50 anomalous suppression

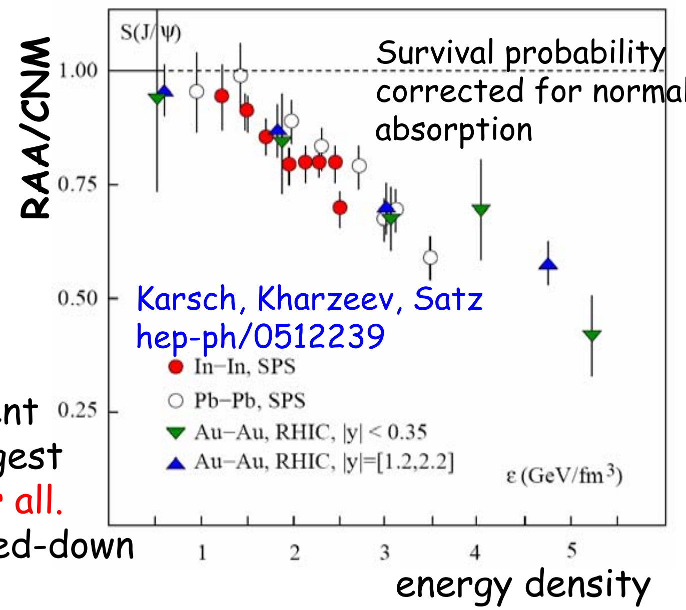






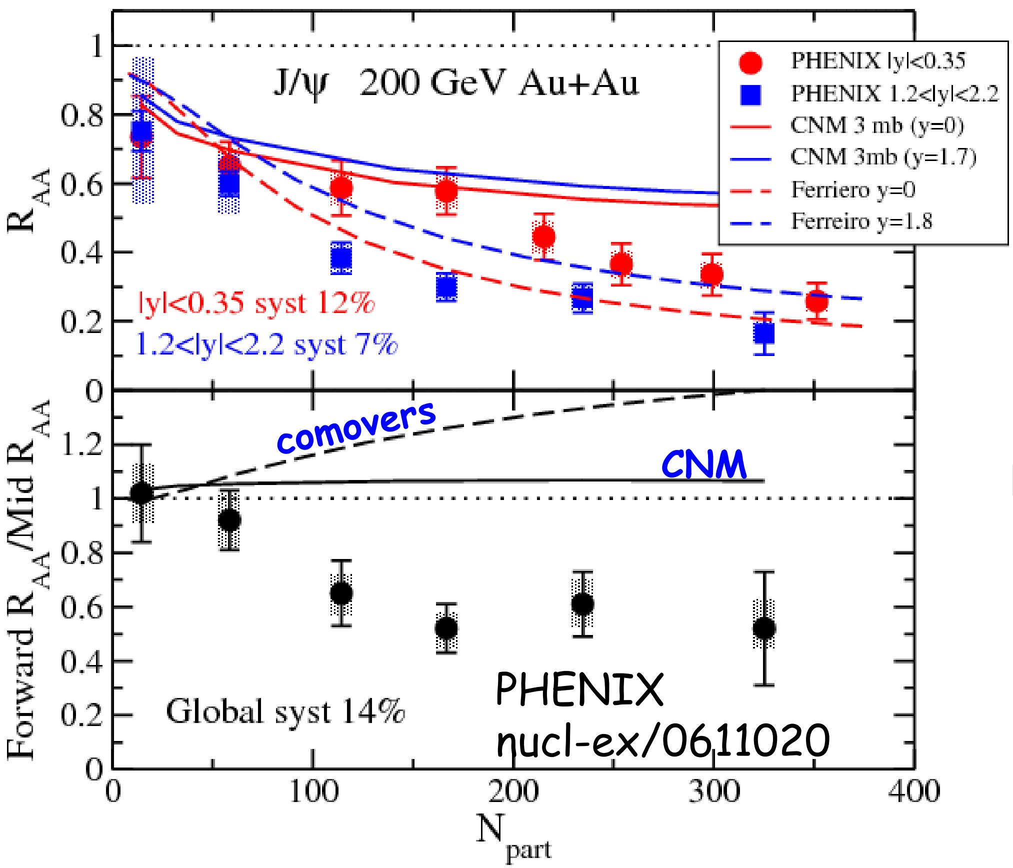
regeneration models give enhancement that compensates for screening?

on the other hand, recent lattice calculations suggest J/ψ not screened after all. Suppression only via feed-down from screened χ_C & ψ'

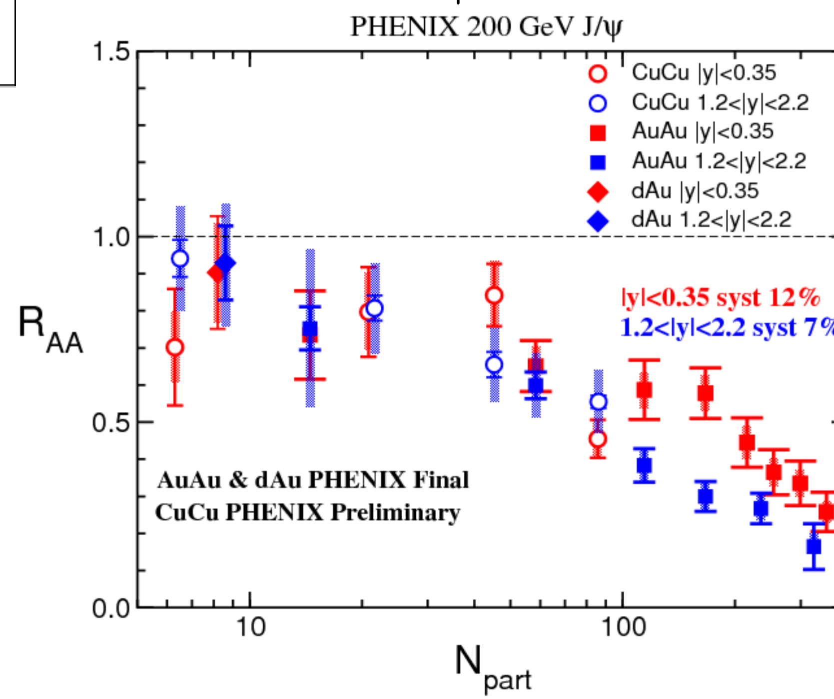


PHENIX Run4 AuAu final results (nucl-ex/0611020)
1st high statistics J/ψ measurements at RHIC

- most central collisions suppressed to ~0.2
- forward suppressed more than mid-rapidity
  - saturation of forward/mid suppression ratio rapidity @ ~0.6 for $N_{part} \geq 100$?
  - trend opposite to that of CNM (solid lines) and comover (dashed) models

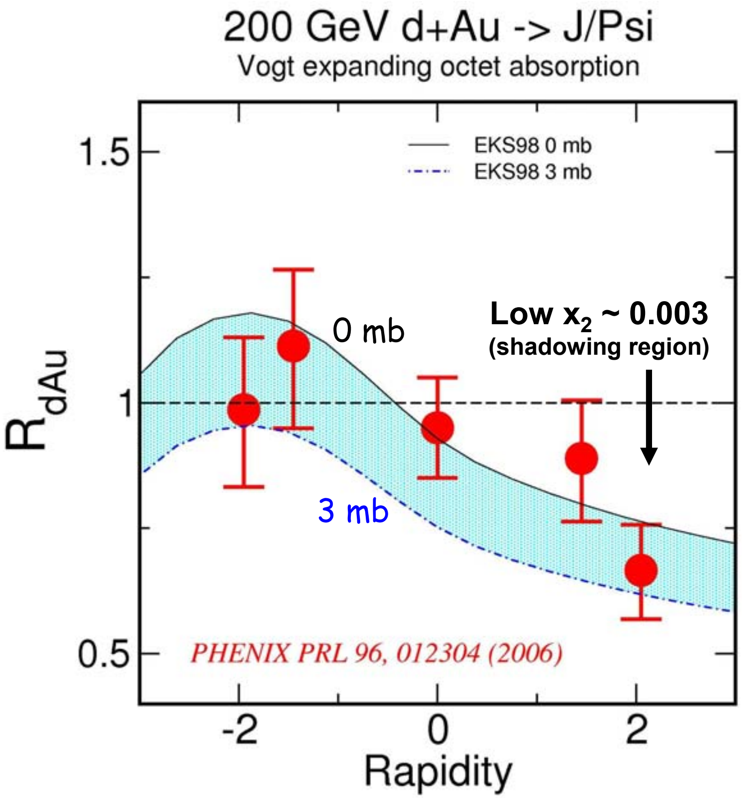


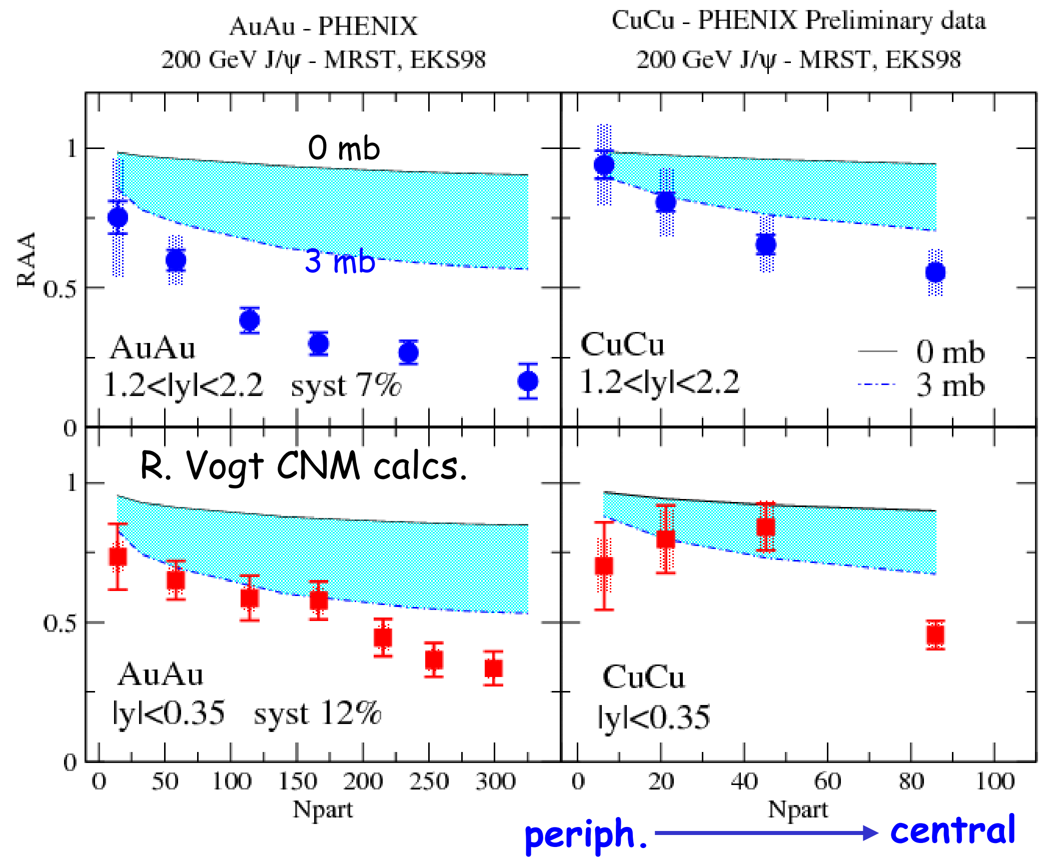
Also CuCu preliminary results (open circles) follow AuAu trend vs centrality for N_{part} below ~100



J/ψ suppression in AA collisions & CNM baseline

(CNM = Cold Nuclear Matter)



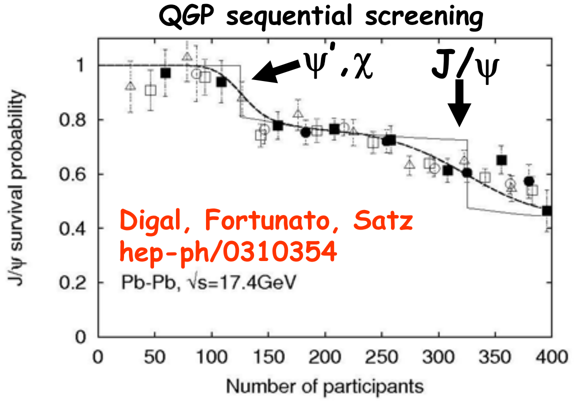


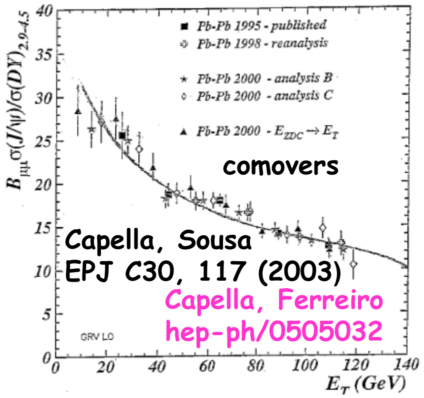
- **CNM calculations with shadowing & absorption – R. Vogt, nucl-th/0507027**
- **present dAu data probably only constrains absorption to: σ_{ABS} ~ 0-3 mb**

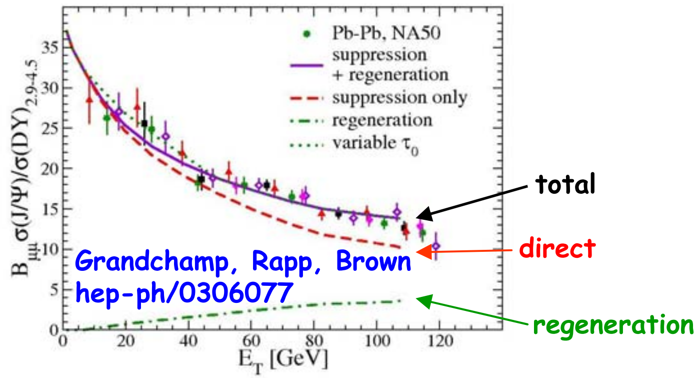
See also talks by R. Vogt & R. Granier de Cassagnac Saturday (2.1) & Sunday(3.1) afternoons

- **AuAu suppression is stronger than CNM calculations predict especially for most central mid-rapidity & at forward rapidity**

Models without regeneration



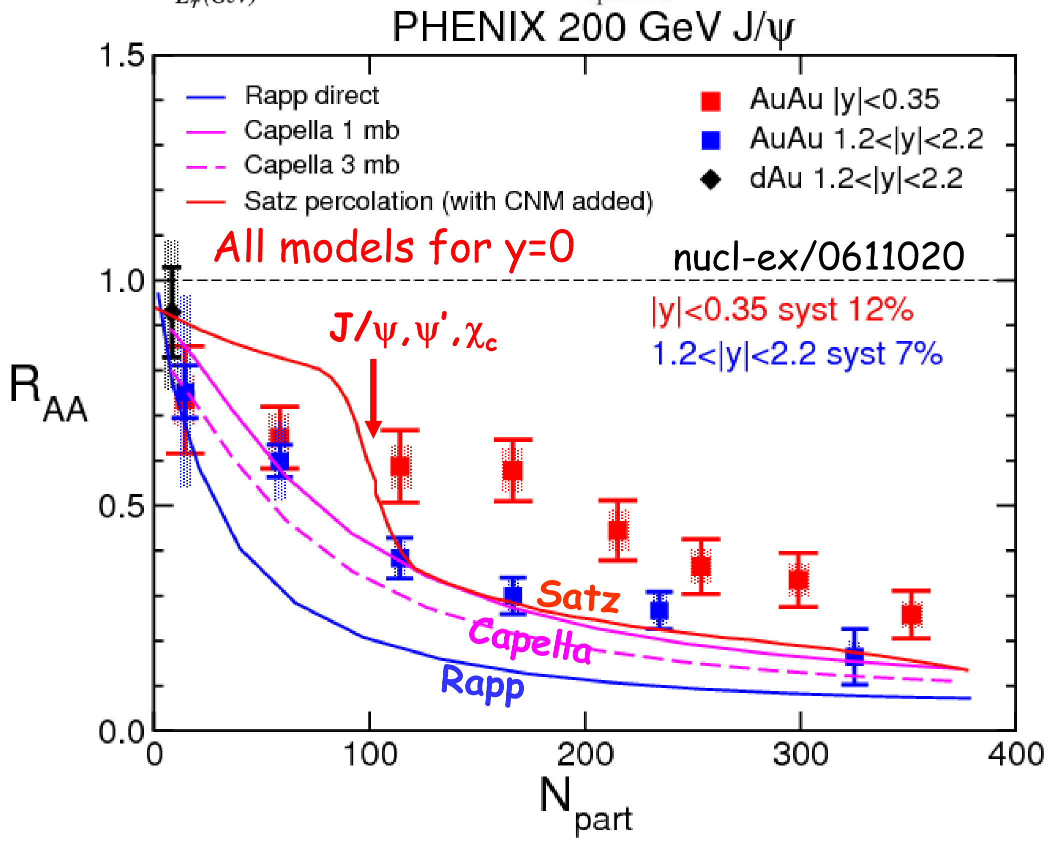




Models that reproduce NA50 results at lower energies (above):

- Satz – color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)
- Capella – comovers with normal absorption and shadowing
- Rapp – direct production with CNM effects (without regeneration)

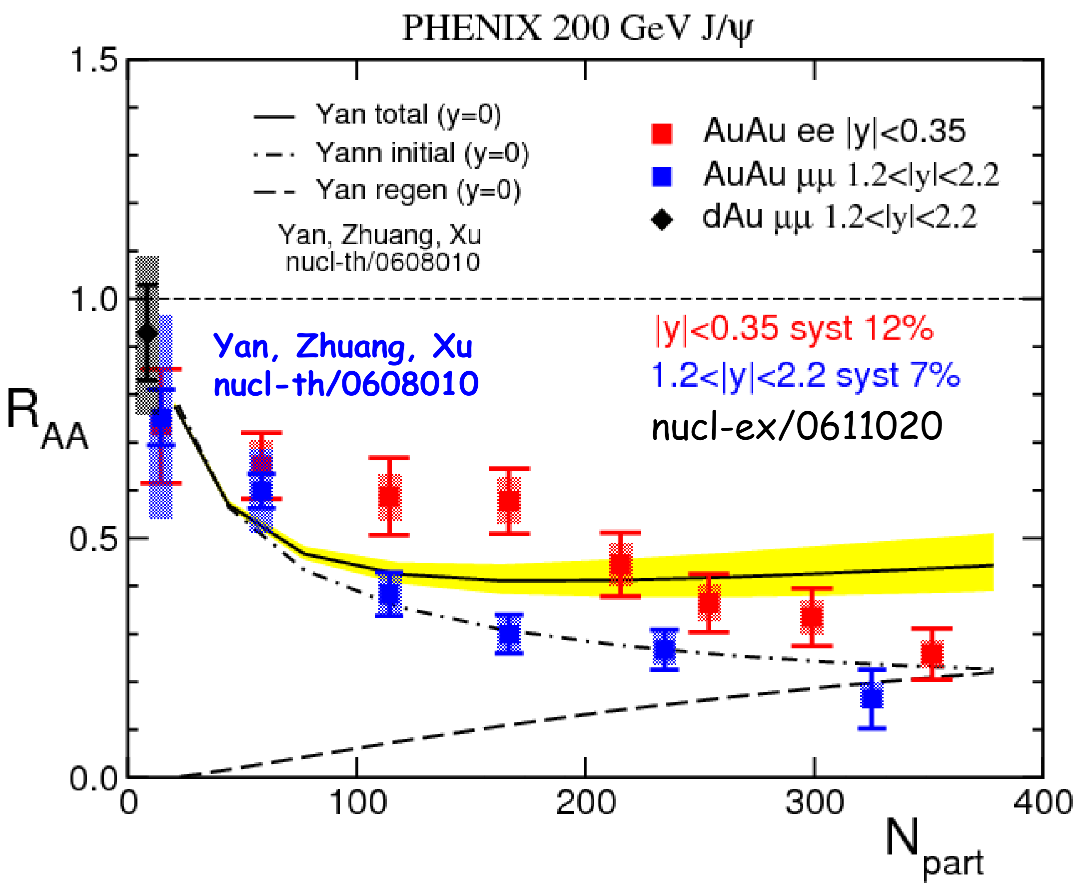
But predict too much suppression for RHIC mid-rapidity (at right)!



Regeneration

At RHIC with 10x collision energy & 2-3x gluon energy density relative to SPS → stronger QGP suppression at RHIC expected

- in regeneration models single charm quarks combine in the later stages to form J/ψ's
- can compensate for strong QGP suppression to come near y=0 RHIC data
- regeneration would be much larger at the LHC !
- but this regeneration goes as the (single) charm density which is poorly known at RHIC (another story, see A. Suaide's talk)



Sequential Screening

(Karsch, Kharzeev, Satz, hep-ph/0512239)

Sequential screening only of the higher-mass resonances that feed-down to the J/ψ; with the J/ψ itself still not dissolved?

- supported by recent Lattice calculations that give $T_{J/\psi} > 2\ T_C$
- gives similar suppression at RHIC & SPS (for mid-rapidity)

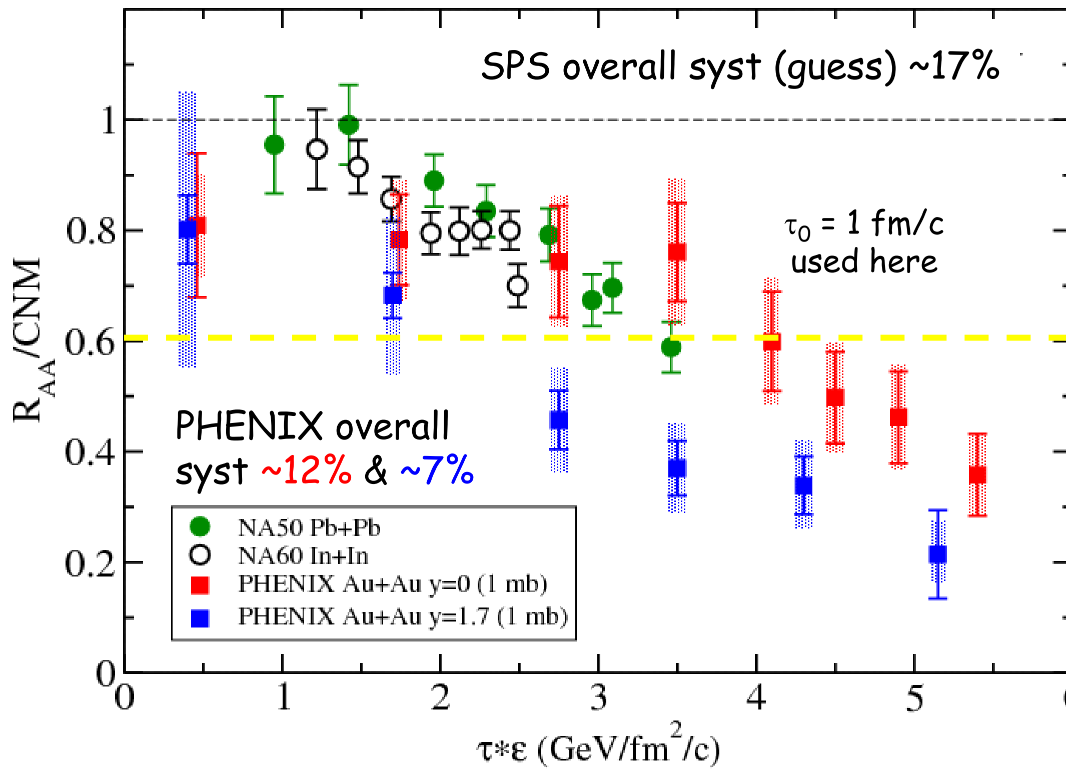
Quarkonium dissociation temperatures – Digal, Karsch, Satz

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

But carefull! Hard to know how to set relative energy density for RHIC vs SPS

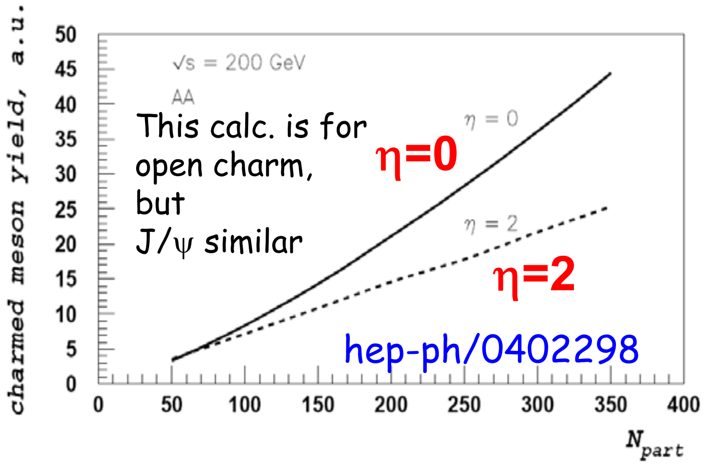
$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

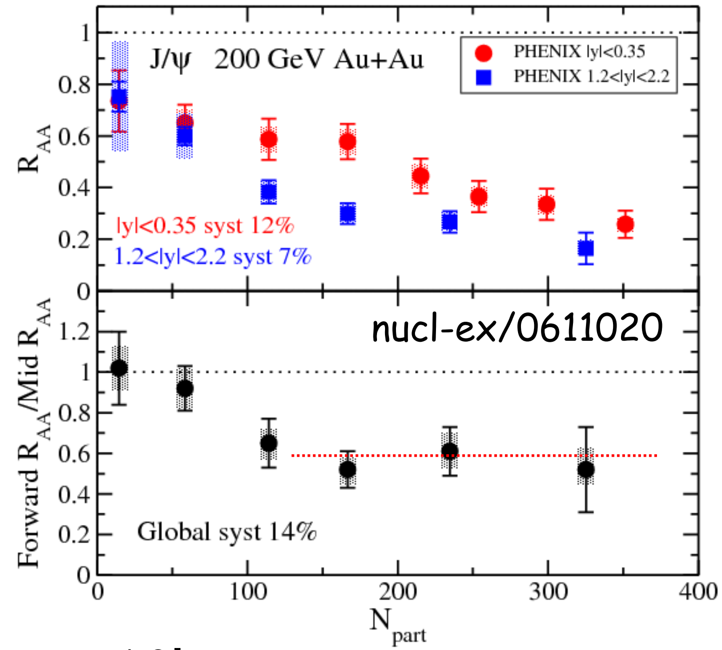
- τ_0 > 1 fm/c @ SPS?
  - 1.6 fm/c crossing time
- τ_0 smaller @ RHIC?



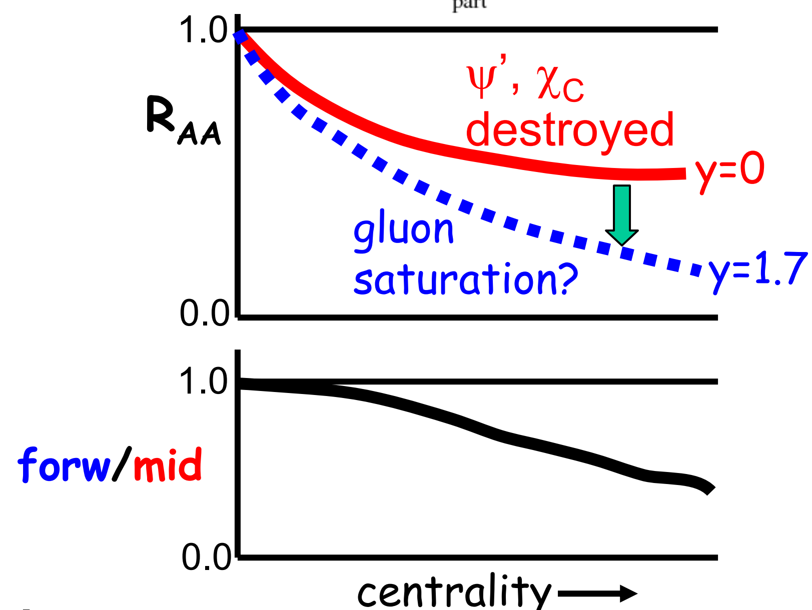
- Suppression stronger than possible from ψ', χ_C alone?
- Gluon saturation can lower forward relative to mid-rapidity?

Sequential Screening Scenario





- QGP suppression of χ_C, ψ'
- + additional forward suppression from gluon saturation (CGC)
- but approx. flat forward/mid above N_{part} ~ 100 seems inconsistent – forward should drop more for more central collisions as gluon saturation increases



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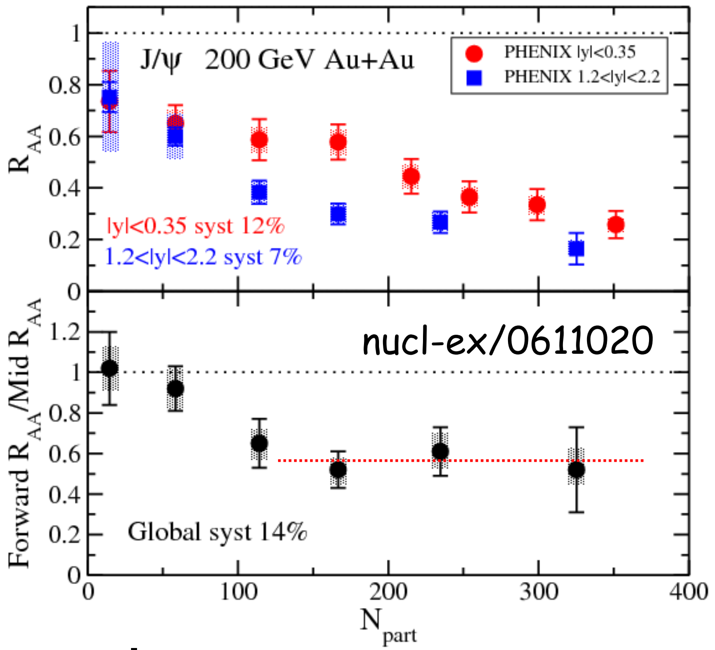
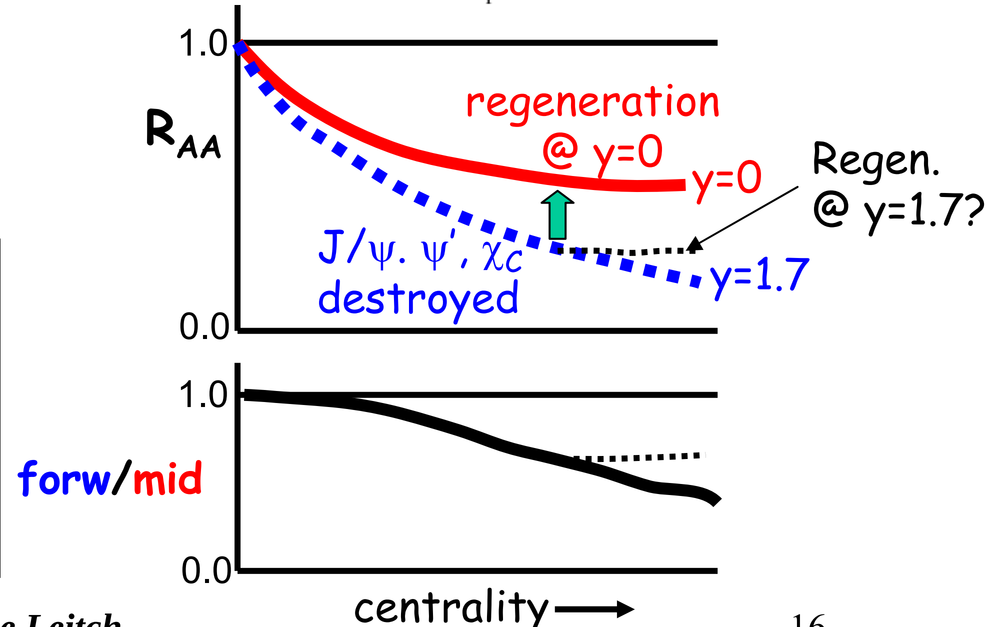
Regeneration Scenario

• both forward & mid rapidity suppressed by QGP – i.e. screening or large gluon density
• mid-rapidity suppression reduced by strong regeneration effect
• but approx. flat forward/mid suppression for N_{part}>100 seems inconsistent with increasing regeneration & increasing QGP suppression for more central collisions





Need comprehensive theoretical work that puts sequential screening, regeneration, gluon saturation, forward suppression of open charm, etc. ALL TOGETHER – and considers experimental uncertainties carefully

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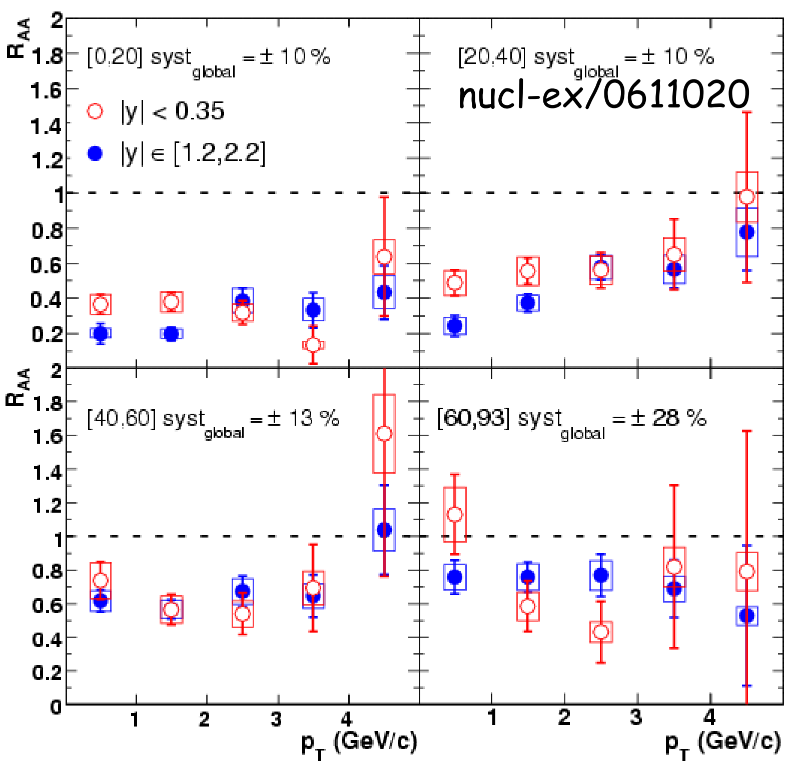
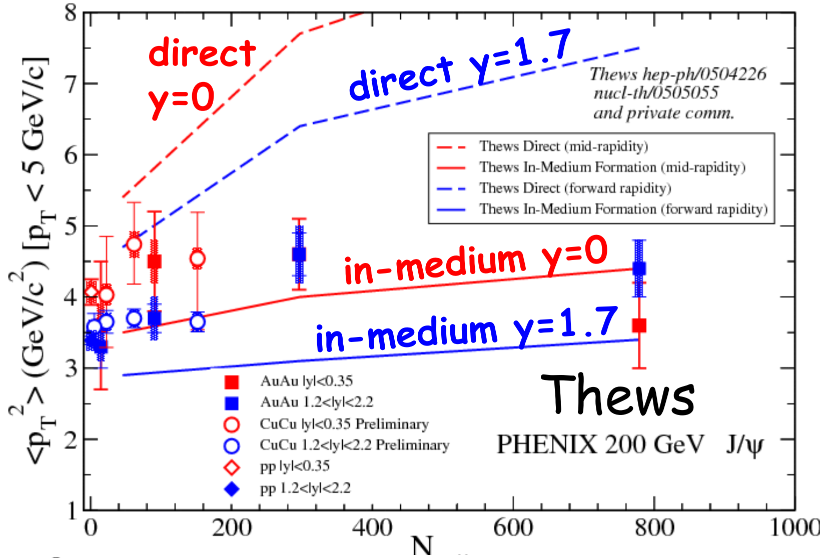
Regeneration should cause narrowing of p_T – does it?

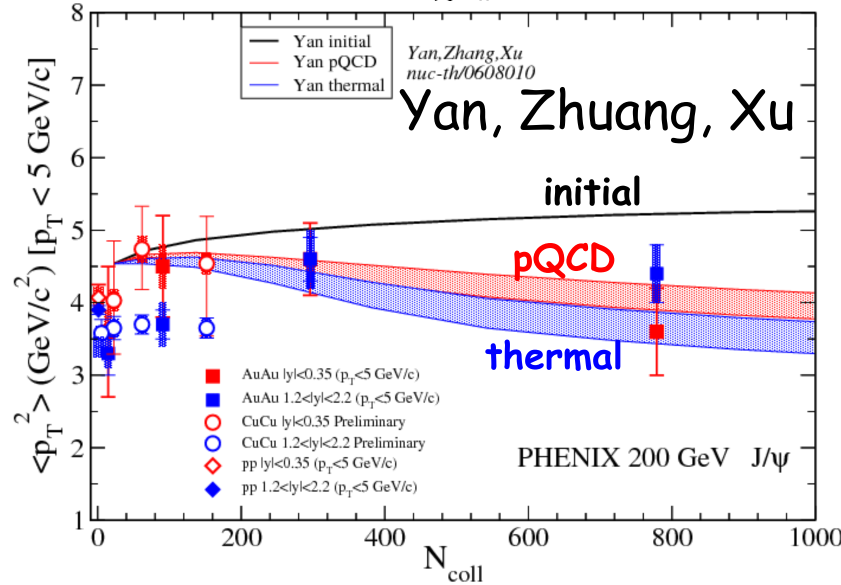
$\langle p_T^2 \rangle$ pretty flat for both mid and forward-y

- as expected in regeneration picture of Thews
- Yan picture almost flat to start with, gives slight fall-off with centrality

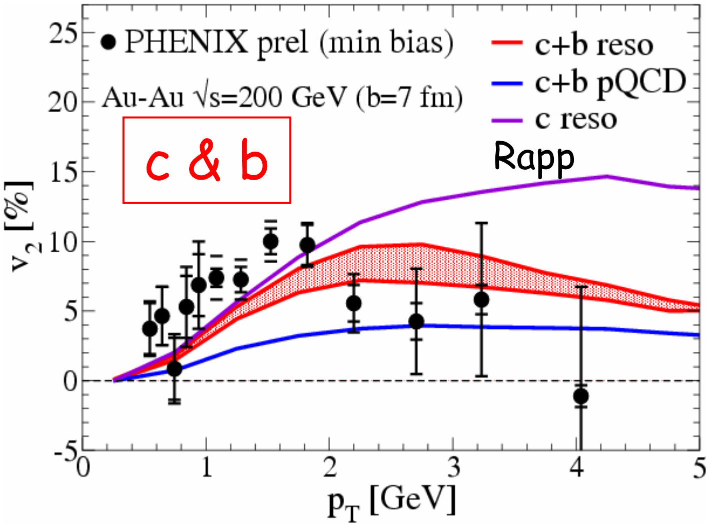
Caution - $\langle p_T^2 \rangle$ from fits often unreliable for AA (stable when restricted to p_T<5 GeV/c here)
Better for theoretical comparisons to look at $R_{AA}(p_T)$?





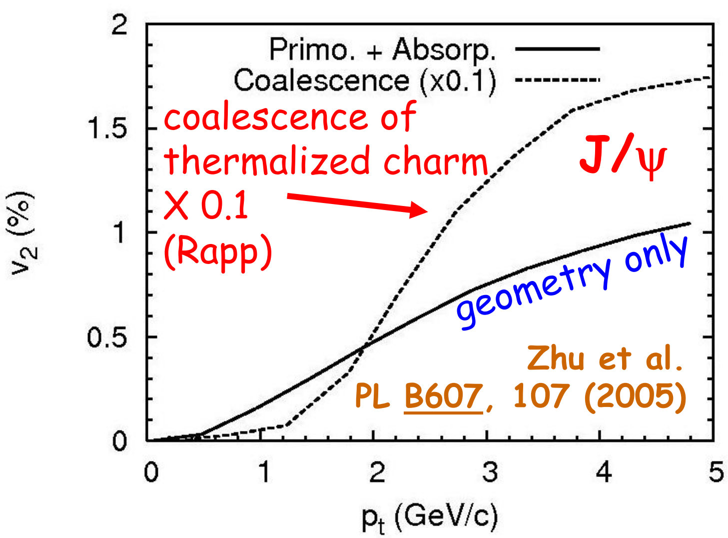


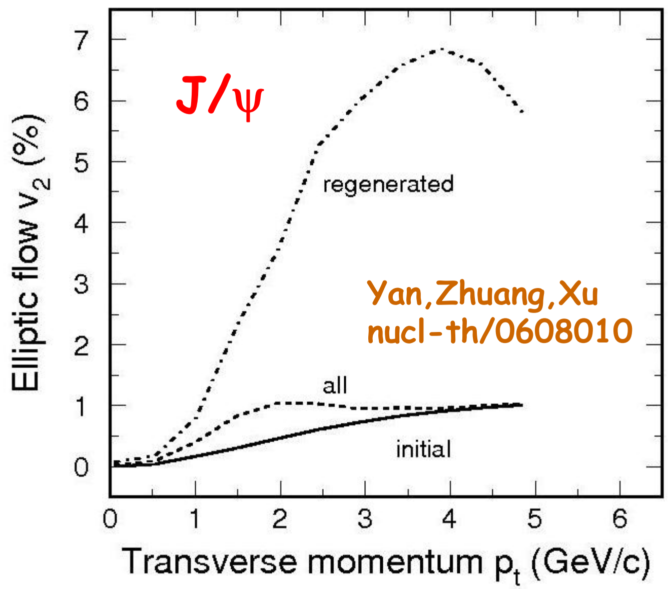
Regeneration should give J/ψ Flow



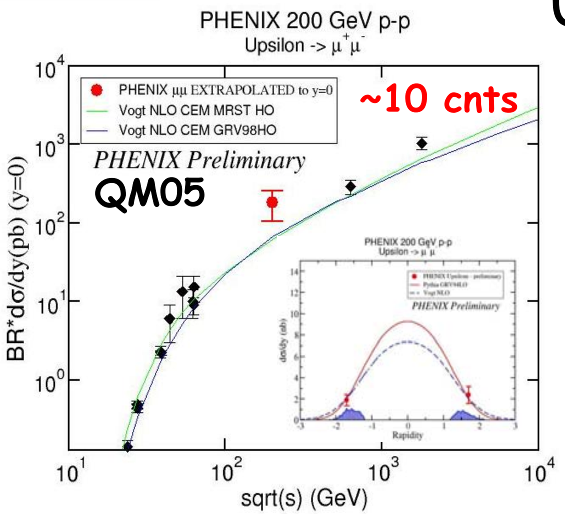
Open charm has recently been seen to flow (at least at some p_T values)

Need to look for J/ψ flow – if regeneration dominates, the J/ψ's should inherit flow from charm quarks



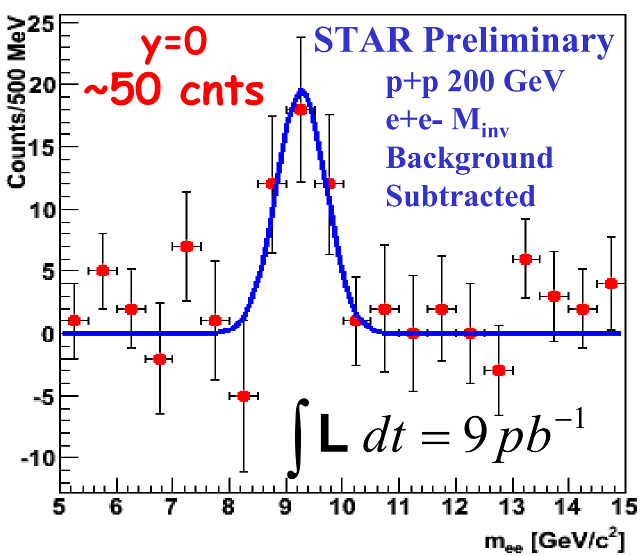


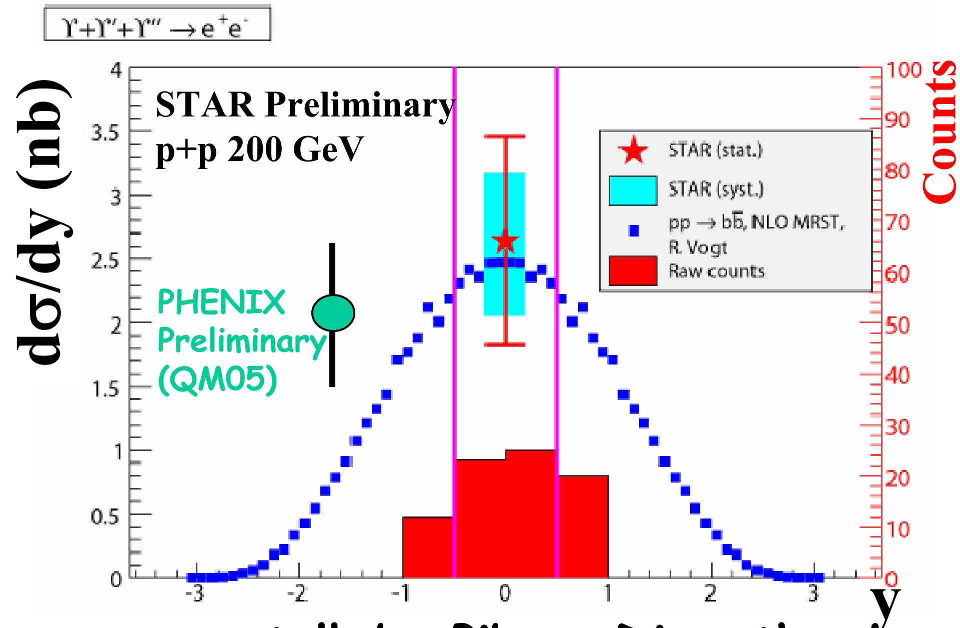
Upsilons at RHIC



Signal	RHIC Exp. (Au+Au)	RHIC I (>2008)	RHIC II	LHC ALICE+
$J/\psi \rightarrow e^+e^-$	PHENIX	3,300	45,000	9,500
$J/\psi \rightarrow \mu^+\mu^-$		29,000	395,000	740,000
$\Upsilon \rightarrow e^+e^-$	STAR	830	11,200	2,600
$\Upsilon \rightarrow \mu^+\mu^-$	PHENIX	80	1,040	8,400

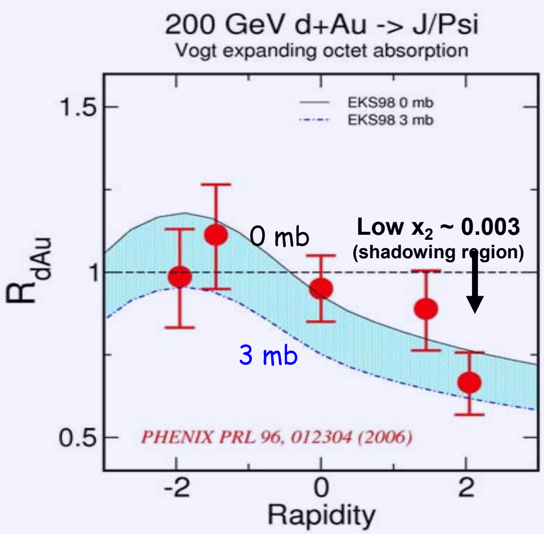
PHENIX QM05 - 1st Upsilons at RHIC from ~3pb^{-1} collected in the 2005 run.





see talk by Pibero Djawotho Sunday afternoon, 3.1

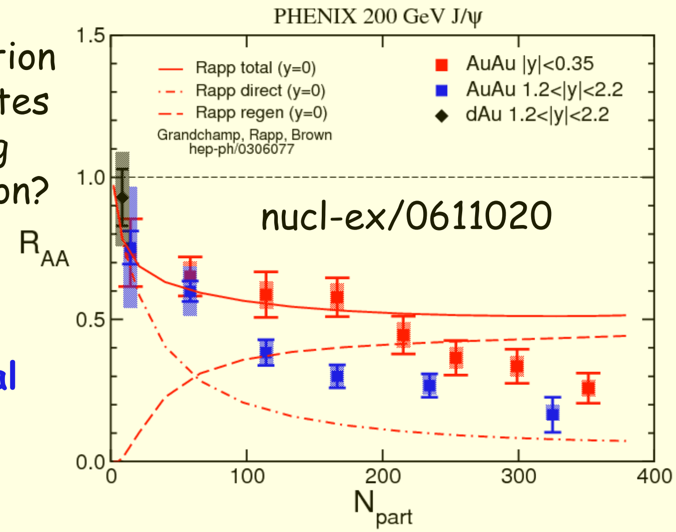
Summary – J/ψ Suppression
A puzzle of two (or more) ingredients



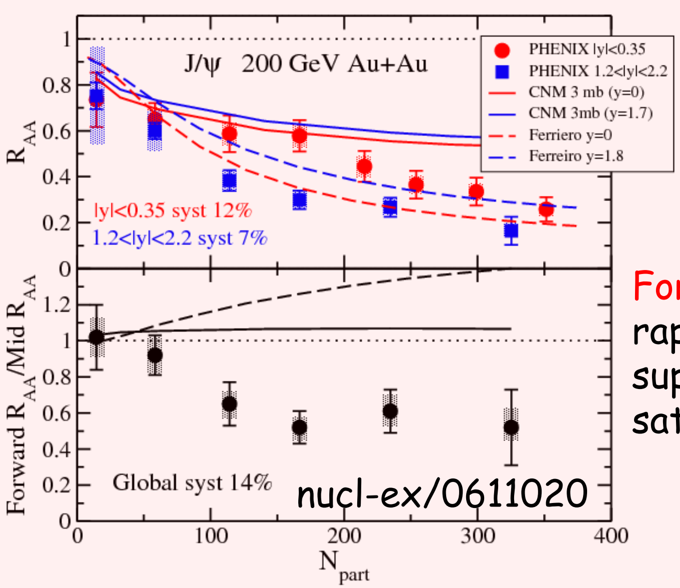
CNM needs better data constraint

Experimental homework

Regeneration compensates for strong destruction?



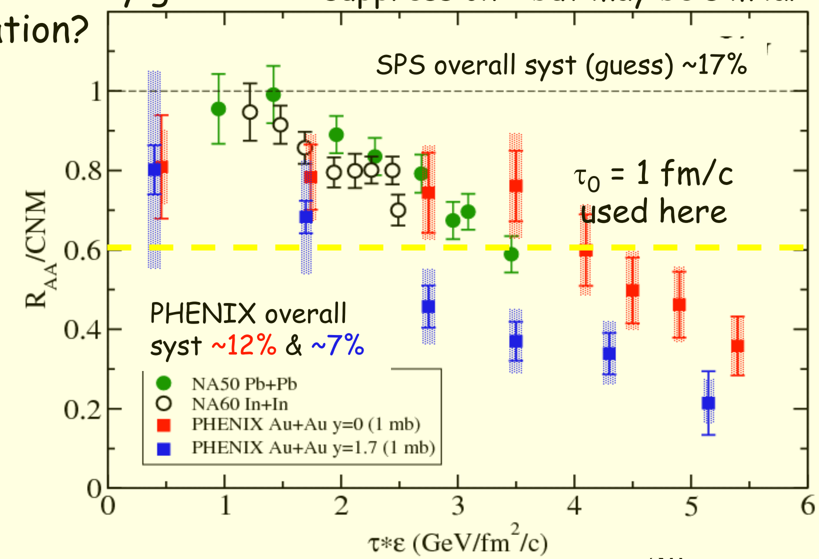
Theoretical homework



Forward/mid rapidity suppression ratio saturates @~0.6

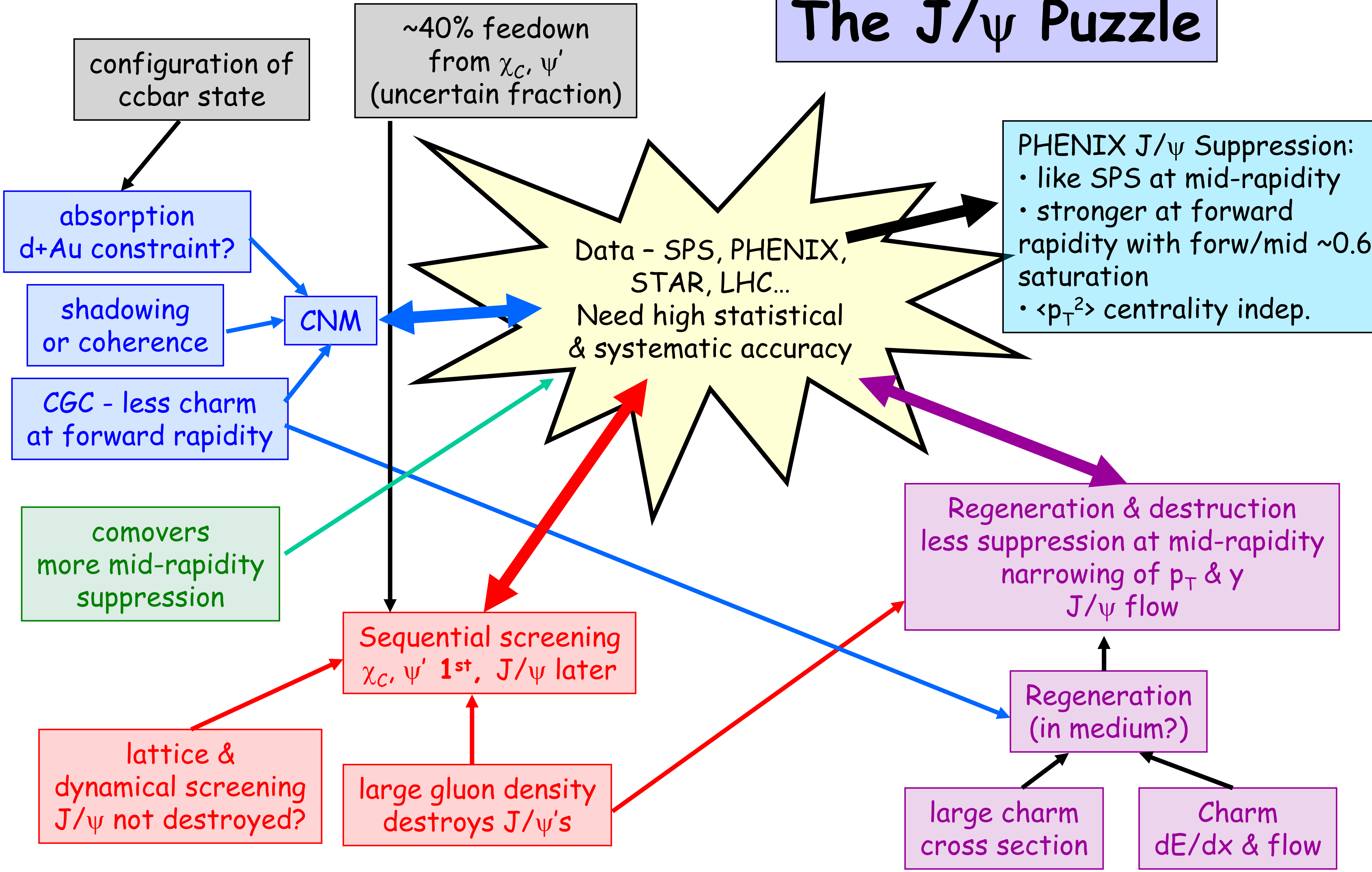
Sequential screening and forward-y gluon saturation?

difficult to compare RHIC to SPS suppression – but may be similar

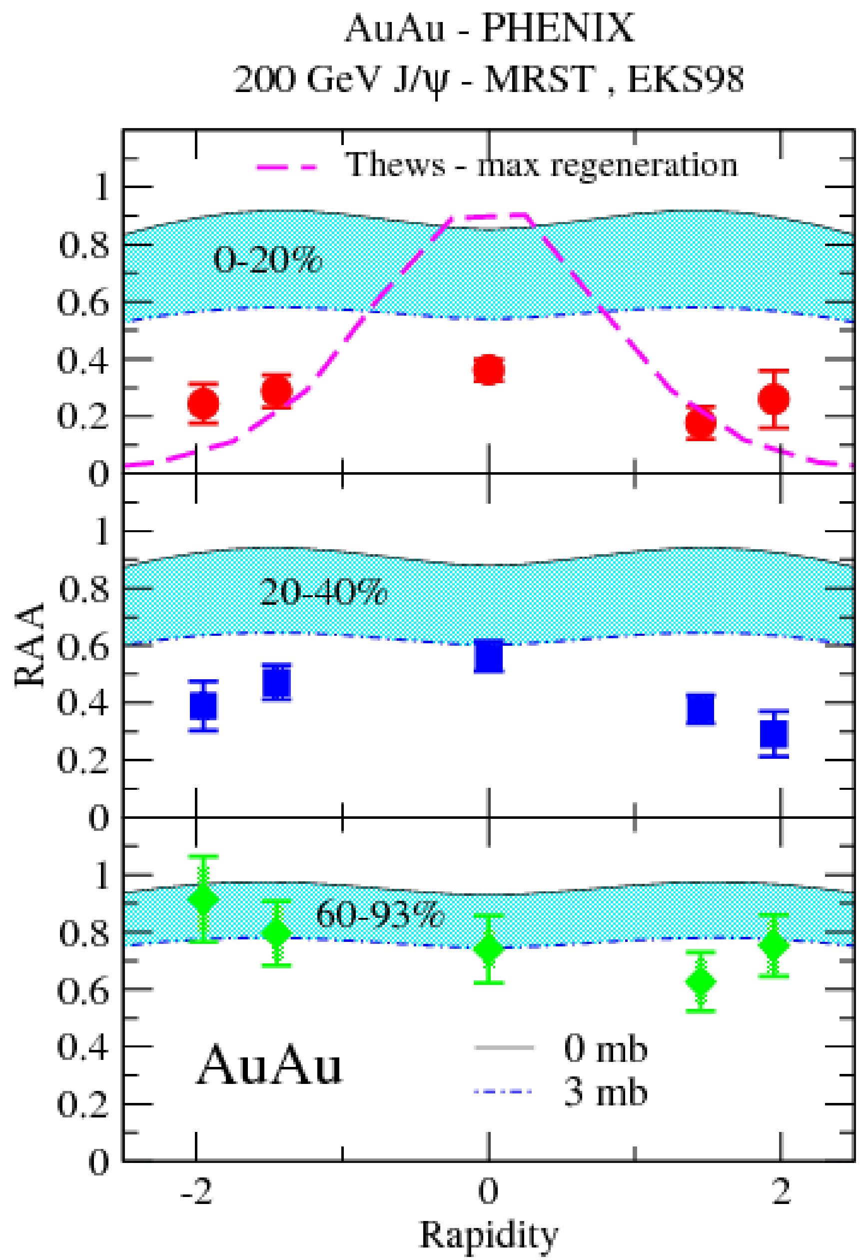


BACKUP

The J/ψ Puzzle

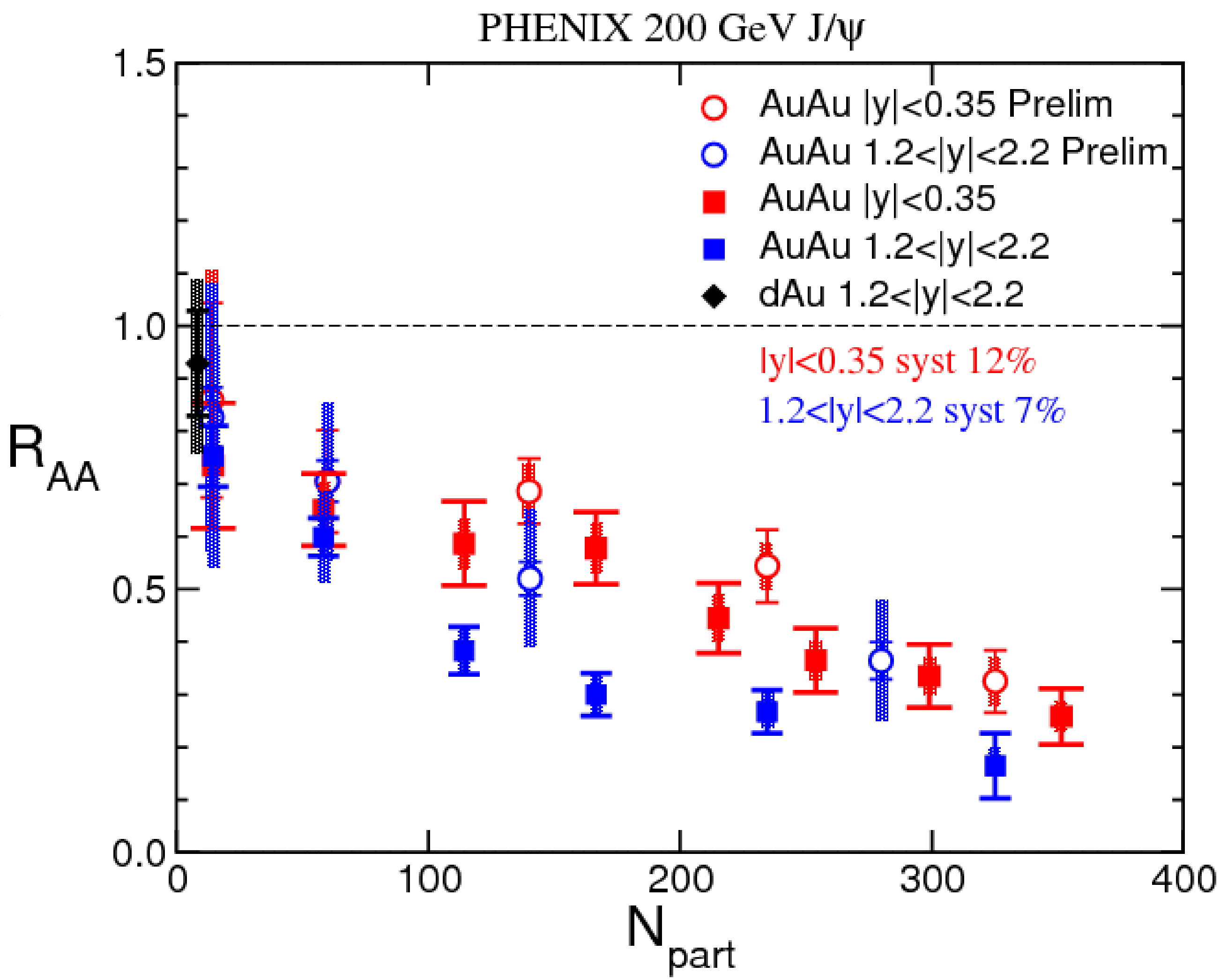


CNM effects, constrained by dAu data, give fairly flat rapidity dependence in AuAu

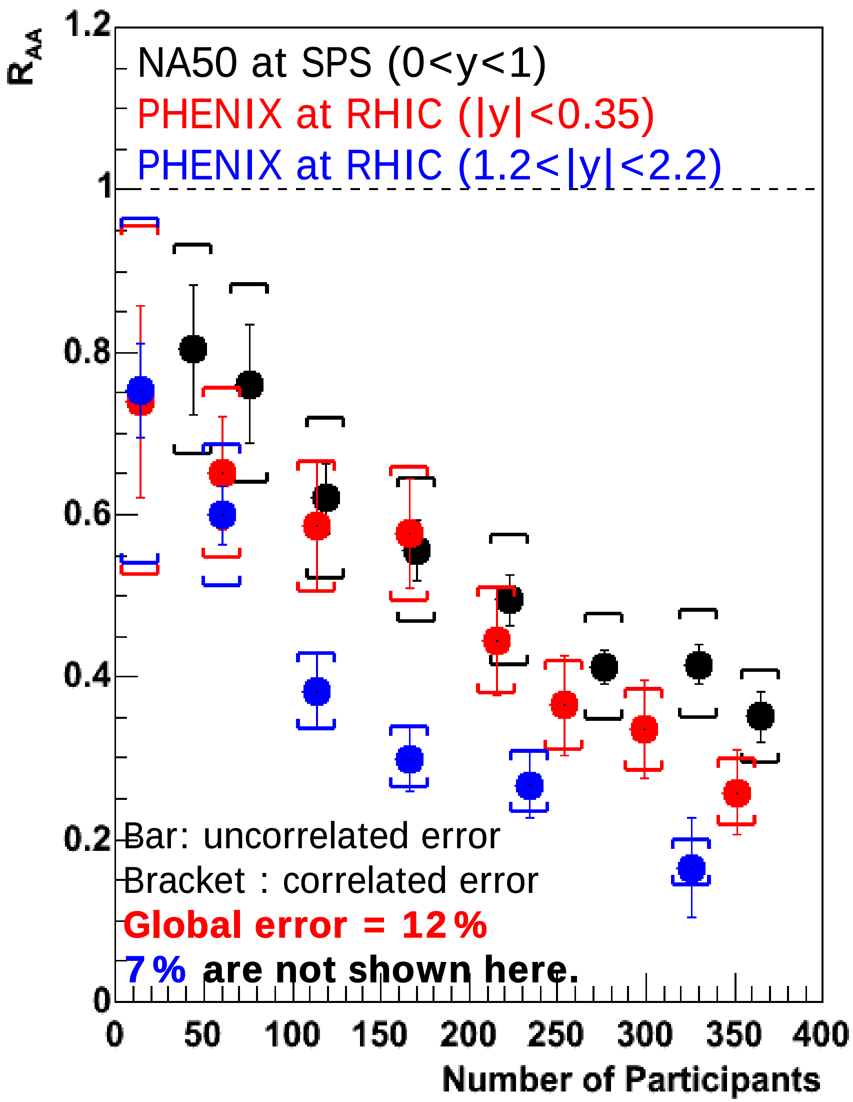


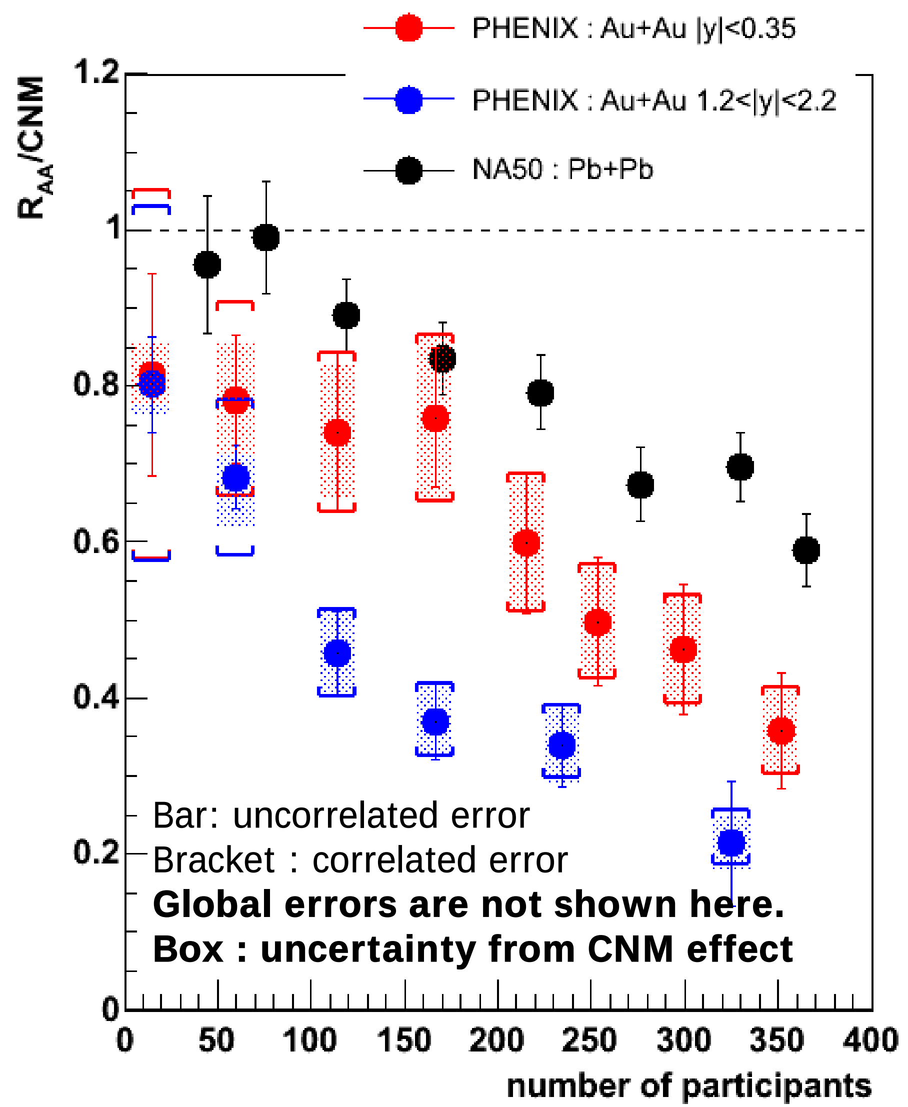
Comparison of QM05 preliminary AuAu results (open circles) to final results (closed circles).

Red mid rapidity
Blue forward rapidity

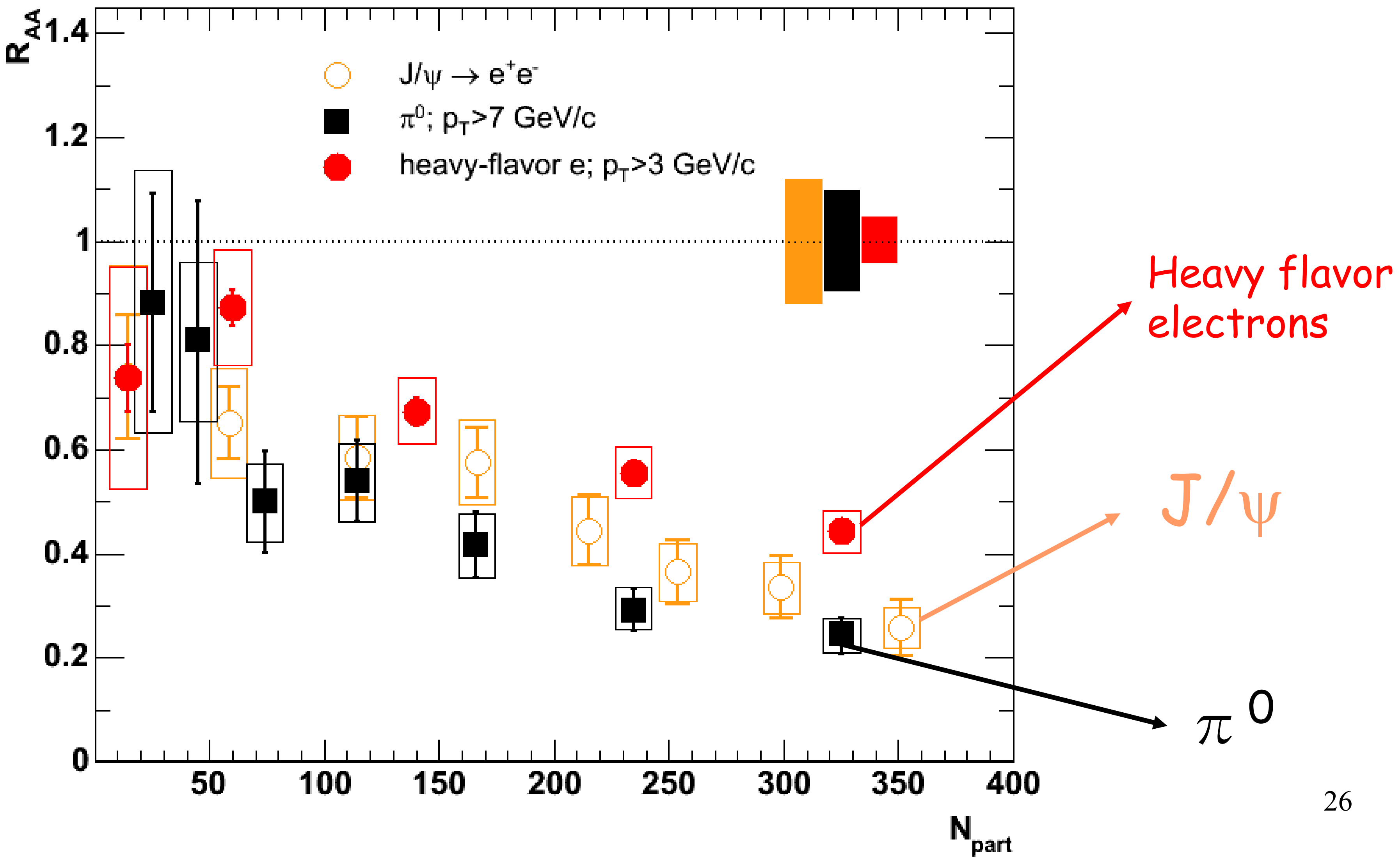


R_{AA} or R_{AA}/CNM vs Number of Participants





J/ψ suppression vs. light hadrons



Many More Models for RHIC J/ψ suppression in AuAu Collisions

All have suppression + various regeneration mechanisms

Rapp – PRL 92, 212301 (2004)
- screening & in-medium production

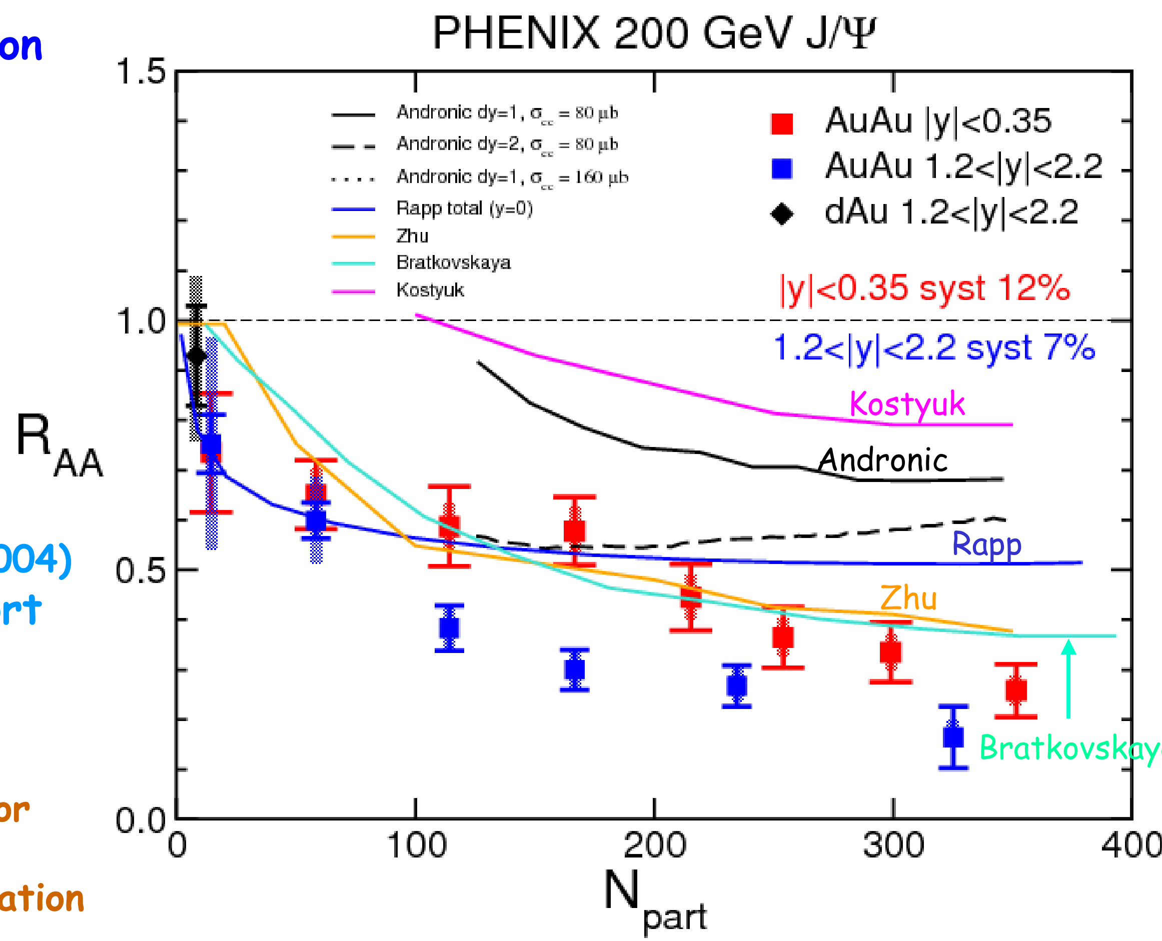
Thews – see previous slide

Andronic - PL B57, 136 (2003)
- statistical hadronization model
- screening of primary J/ψ's
- + statistical recombination of thermalized c-cbar's

Kostyuk – PRC 68, 041902 (2003)
- statistical coalescence
- + comovers or QGP screening

Bratkovskaya – PRC 69, 054903 (2004)
- hadron-string dynamics transport

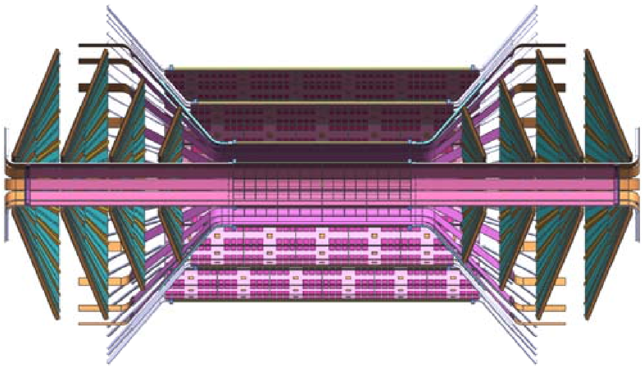
Zhu - PL B607, 107 (2005)
- J/ψ transport in QGP
- co-movers, gluon breakup, hydro for QGP evolution
- no cold nuclear matter, no regeneration

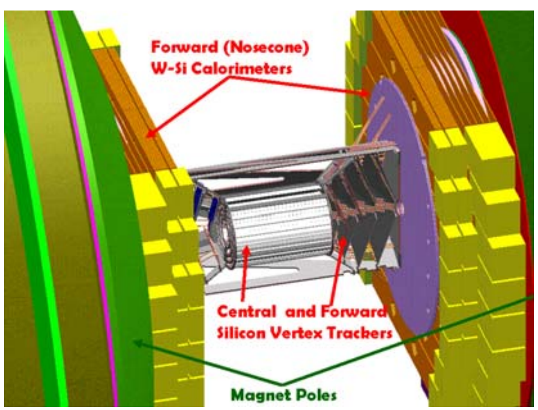


Detector Upgrades for Heavy Quarks

PHENIX

- Silicon vertex detector
  - mid-rapidity & forward heavy-q's, incl. B $\rightarrow$ J/ψ X
  - improved background & mass resolution for quarkonia & dimuons
- Nose cone calorimeter $\chi_C \rightarrow$ J/ψ γ



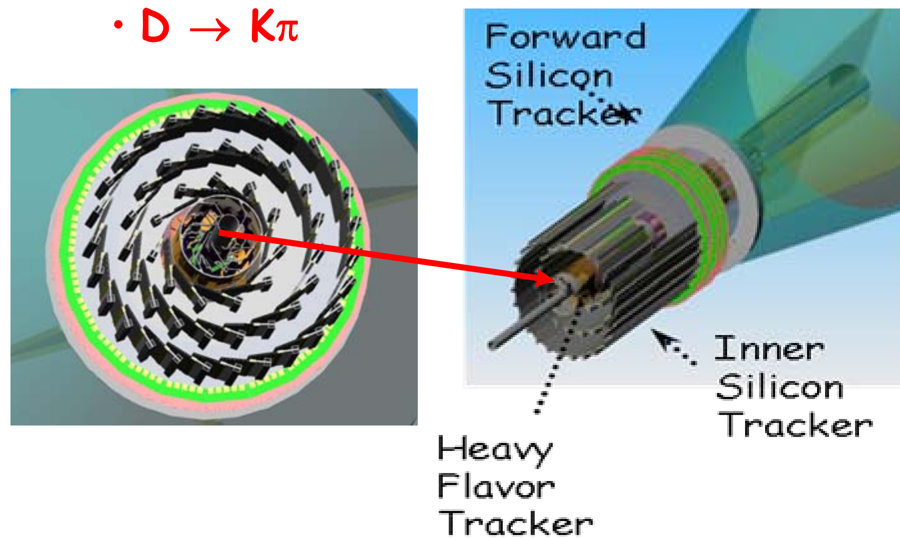


RHIC-II

- Luminosity increases via electron cooling also important:
  - x10 (AuAu); x2-3 (pp)

STAR

- Silicon vertex detectors
- Heavy Flavor Tracker & integrated central tracker
- **D $\rightarrow$ Kπ**



Los Alamos

RHIC-II - Quarkonia

- With detector upgrades (PHENIX and STAR):
  - J/ψ from B decays with displaced vertex measurement (both).
  - Reduce $J/\psi \rightarrow \mu\mu$ background with forward vertex detector in PHENIX.
  - Improve mass resolution for charmonium and resolve Υ family.
  - See χ_c by measuring γ in forward calorimeter in front of muon arms (PHENIX)

- And with the luminosity upgrade:
  - Measure $B \rightarrow J/\psi$ using displaced vertex - independent B yield measurement, also get background to prompt J/ψ measurement.
  - J/ψ R_{AA} to high p_T. Does J/ψ suppression go away at high p_T?
  - J/ψ v_2 measurements versus p_T. See evidence of charm recombination?
  - Υ R_{AA}. Which Upsilons are suppressed at RHIC?
  - Measure ψ' R_{AA}. Ratio to J/ψ?
  - Measure $\chi_c \rightarrow J/\psi + \gamma$ R_{AA}. Ratio to J/ψ?

Onia Yields at RHIC II

Signal/System	pp (200 GeV)	pp (500 GeV)	CuCu (200 GeV)	AuAu (200 GeV)	dAu (200 GeV)
$J/\Psi \rightarrow ee$	55,054	609,128	73,921	44,614	29,919
$\Psi'(2S) \rightarrow ee$	993	10,985	1,333	805	540
$\chi\_c0 \rightarrow \gamma + J/\Psi \rightarrow ee$	100	2,578	134	81	54
$\chi\_c1 \rightarrow \gamma + J/\Psi \rightarrow ee$	1,340	40,870	1,800	1,086	728
$\chi\_c2 \rightarrow \gamma + J/\Psi \rightarrow ee$	2,190	59,296	2,941	1,775	1,190
$\Upsilon(0,1,2) \rightarrow ee$	210	3,032	547	397	184
$B \rightarrow J/\Psi \rightarrow ee$	1,237	41,480	4,567	3,572	1,085
$J/\Psi \rightarrow \mu\mu$	468,741	5,483,006	653,715	394,535	258,136
$\Psi'(2S) \rightarrow \mu\mu$	8,453	98,880	11,789	7,115	4,655
$\chi\_c0 \rightarrow \gamma + J/\Psi \rightarrow \mu\mu$	3,822	99,824	5,330	3,217	2,105
$\chi\_c1 \rightarrow \gamma + J/\Psi \rightarrow \mu\mu$	51,215	1,582,561	71,425	43,107	28,204
$\chi\_c2 \rightarrow \gamma + J/\Psi \rightarrow \mu\mu$	83,702	2,296,069	116,732	70,451	46,095
$\Upsilon(0,1,2) \rightarrow \mu\mu$	528	7,723	1,429	1,035	469
$B \rightarrow J/\Psi \rightarrow \mu\mu$	2079	76466	5756	3752	1824

- Precision measurements of the J/Ψ
- Exploratory measurements of the other onium states.
- Steep increase at $\sqrt{s}$ = 500 GeV illustrates the significant difficulties for measurements at lower energies.